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Impact of Indoor Environmental Quality on Occupant Satisfaction, Perceived Health, and Work Performance in “Green” Office Buildings in the Middle East

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Impact of Indoor Environmental Quality on Occupant Satisfaction, Perceived Health, and Work Performance in "Green" Office Buildings in the Middle East

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Declaration I am the author of this thesis, and the work described therein was carried out by myself personally, with the exceptions highlighted in the declaration of authorship preceding each publication.

Abstract

Globally, green-certified buildings (GBs) are promoted as an effective solution to mitigate climate change challenges, saving energy, and delivering better Indoor Environment Quality (IEQ). However, the actual role of green certification in improving the quality of indoor environment and improving occupant satisfaction is much debated. There is a concern that GBs may succeed in achieving energy efficiency targets but may exhibit unintended consequences that reduce the quality of indoor environment and curtail occupant satisfaction, health, and work performance.

In the Middle East (ME), the number of green-certified buildings is increasing rapidly and associated with an increase in the number of localised Green Building Codes (GBCs). However, to date, no systematic research has evaluated the actual performance of IEQ in green buildings in this region. Hence, this thesis is designed to examine whether the IEQ of green office buildings in the ME meets the standards-recommended ranges of thermal comfort and indoor air quality (IAQ) that identified by GBCs, and if so, to what extent they are perceived satisfied by their occupants.

This thesis starts with examining the role of localised GBCs in improving the performance of IEQ. This is achieved through a longitudinal field study, we follow 120 occupants who transitioned from four conventional office buildings (CBs) to the first GB, designed to the local Jordanian Green Building Guide (JGBG). The repeated-measures protocol (pre- and post-move) is used. Measures cover physical parameters (i.e., air temperature, relative humidity, and indoor CO_2 levels), subjective parameters (i.e., occupants' satisfaction, self-reported Sick Building Syndrome symptoms (SBS)), and occupant thermal comfort. Alongside this, instantaneous measures for temperature, mean radiant temperature, air speed, and relative humidity were conducted for compliance. Results show that moving from CBs to the JGBG-certified building does not improve the occupant satisfaction of IAQ, lighting and acoustic comfort and associated with an increase in the prevalence of SBS symptoms. Further, both building types fail the ASHRAE 62.1 threshold of 20%, so can be labelled as "sick" buildings.

Next, this thesis expands the evaluation to include the green-certified office buildings designed to the international LEED standard. It compares CBs and LEED-certified buildings in terms of the performance of IEQ, occupant satisfaction and work performance. A cross-sectional study design with between-subjects comparison is followed. Further, continuous measures for temperature, relative humidity and CO_2 are adopted, covering 13 office buildings and 502 occupants. In addition, semi-structured interviews are conducted to gain in-depth information about green design motivation and features. Data were collected between summer 2017 and winter 2019 in Jordan. Results show that although LEED buildings comply with recommended ranges of thermal comfort and CO_2 levels, occupant satisfaction with IEQ aspects was significantly lower compared to occupants in CBs, while no significant difference in absenteeism and presenteeism was reported between building types. Over half of those surveyed in LEED buildings and CBs reported IAQ, ventilation and thermal comfort as important issues that need to be improved.

Finally, this thesis investigates the suitability of the applied thermal comfort standards in predicting occupant thermal sensation in air-conditioned buildings in the ME. This is achieved using three approaches. A meta-analysis is used to aggregate outcomes of existing thermal comfort research in the ME to identify challenges faced by occupants in air-conditioned buildings. This is followed by seven thermal comfort field surveys covering 31 air-conditioned buildings and 1,101 occupants in four countries in the ME. Finally, energy model simulations are carried to estimate any potential energy saving in the building energy demand for space cooling in air-conditioned buildings in the surveyed countries. Results demonstrate a clear gap between thermal comfort models and observed thermal sensation of occupants in air-conditioned buildings (i.e., CBs and GBs) in the ME. During the cooling season, the PMV model fails to predict the thermal sensation of 94% of occupants. The monitored thermal conditions in surveyed buildings complied with standards recommended ranges for 58% of the time, and only 40% of occupants find these conditions comfortable. This thesis provides the empirical evidence of overcooling in summer, as 39% of surveyed occupants expressing cold discomfort, which is associated with an increased energy demand for space cooling up to 20% compared to non-overcooled conditions.

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To my loving son, Mahmoud H. Alabbadi

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List of Abbreviations

Abbreviation	Explanation
IEQ	Indoor Environment Quality
IAQ	Indoor Air Quality
POE	Post Occupancy Evaluation
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ISO	International Organization for Standardization
SBS	Sick Building Syndrome
A_A	Absolute Absenteeism
A_R	Relative Absenteeism
P_A	Absolute Presenteeism
P_R	Relative Presenteeism
VOCs	Volatile Organic Compounds
TFA	Total Floor Area
PPD	Predicted Percentage of Discomfort
PMV	Predicted Mean Vote
TSV	Thermal Sensation Vote
TPV	Thermal Preference Vote
Bldg.	Building
Bldg. Type	Building Type
GB	Green Building
CB	Conventional Building
NV	Natural Ventilation
HVAC	Heating, Ventilation, and Air-Conditioning
MM	Mixed-Mode Ventilation
CDD	Cooling Degree-Days
HDD	Heating Degree-Days
GBCs	Green Building Codes
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
PBRS	Pearl Building Rating System
JGBG	Jordanian Green Building Guide
JGBC	Jordanian Green Building Council
QSAS	Qatar Sustainability Assessment System
GSAS	Global Sustainability Assessment System
GPRS	Green Pyramid Rating System
PGBG	Palestinian Green Building Guide
WGBC	World Green Building Council
USGBC	United States Green Building Council
HWP	Health and Work Performance
WHO	World Health Organization
EPBD	Energy Performance of Buildings Directive
OECD	Organization for Economic Co-Operation and Development
ME	Middle East

List of Abbreviations

UK	United Kingdom
US	United States

List of Nomenclature

Term	Description	Unit
V_a	Air Movement Speed	ms^{-1}
RH	Relative Humidity	%
clo	Clothes Thermal Insulation Value	clo
met	Metabolic Rate	met
T_a	Air Temperature	°C
T_o	Operative Temperature	°C
T_r	Mean Radiant Temperature	°C
T_g	Globe Temperature	°C
T_{out}	Outdoor Air Temperature	°C
RH_{out}	Outdoor Relative Humidity	%
T_n	Neutral Temperature	°C
$T_{n(PMV)}$	Neutral Temperature derived from PMV	°C
$T_{n(TSV)}$	Neutral Temperature derived from TSV	°C
CO_2	Carbon Dioxide	ppm

List of Terminology

Term	Definition
Green Building	A building that in its design, construction, or operation, increases energy, water, and material efficiency, and reduces the harmful impact on the micro and macro environment. In this thesis, green buildings referred to the green-certified buildings that achieve the requirements of green building design and they attain a green building certification.
Conventional Building	Refers to the building which is built according to the national construction and building codes.
Indoor Environment Quality	The quality of environment in terms of occupant health and wellbeing. IEQ comprises of four aspects: indoor air quality, thermal, visual, and acoustic comfort.
Indoor Air Quality	Is one of the IEQ aspects and related to pollutants (e.g., biological, chemical, and physical) within indoor environment of building, which have impact on occupant health.
Green Building Code	A kit used to provide an objective evaluation of the 'greenness' of building.
Localised Green Building Codes	Are adopted from leading and widely used international codes, such as BREEAM and LEED. Localised codes are customised to overcome the regional challenges and accommodate specific local context (e.g., economic level, climatic and geographic conditions).
Perceived Comfort	Refers to how comfortable an occupant is with the physical environmental features.

Satisfaction	It implies a state of mind that is driven by gratification from a need or desire as it affects or motivates behavior.
Work Performance	A measure indicating how an employee is performing against the expected work tasks by employer or compared to other employees working in a similar job.
Absenteeism	The average number of employee days lost per year through illness and unauthorized absences as a percentage of contracted days.
Presenteeism	The practice of being present at workplace but not fully functioning at work because of health issues.
Sick Building Syndrome	A condition that occurs when several building's occupants have a group of medical symptoms without a specific identifiable cause, including headache, eye irritation, dizziness, mental fatigue, and dry skin etc.
Post Occupancy Evaluation	A process of obtaining feedback (objective + subjective) on a building performance in use.

1 Introduction

One of the promised benefits of green office buildings is providing a better quality of the indoor environment for occupants compared to conventional buildings. However, the real performance of IEQ in green buildings and their positive impacts on buildings' users are still much debated. This chapter introduces the overall topic. It also develops the argument that suggests this is an important yet underdeveloped area of research, particularly, in the ME, requiring timely attention. First, the background outlines the concept of green buildings and how GBCs are developed, also, it discusses the potential impact of IEQ on building occupants. Next, the research problem illustrates the knowledge gaps, and how these gaps are translated into the aim and objectives. Then the research scope and thesis structure are presented. Finally, the chapter presents the publications associated with this research. This thesis constitutes of three published papers, that represent the main contribution of this research.

1.1 Background

The concept of green design of a building is defined as practices applied to design a building to increase energy, water, and material efficiency, and curtail the harmful impact of buildings on the micro and macro environments (EPA, 2020). So essentially, when these practices applied correctly, the green buildings may last longer, cost less to operate and increase occupant satisfaction and health (WGBC, 2014).

Over the last two decades, there has been a rapid motive for buildings to be "green" overall the world (WGBC, 2016). This has resulted in developing the localised GBCs, which are adopted from leading and widely used international codes, i.e. BREEAM in the United Kingdom (BREEAM, 2019) and LEED in the United States (USGBC, 2019). Localised codes are customised to overcome the regional challenges and accommodate specific local context (e.g., economic level, climatic and geographic conditions). Green Star in Australia (Green Building Council Australia, 2003), Green Mark in Singapore (Ministry of National Development Singapore, 2021), Pearl Building Rating System in the United Arab Emirates (Abu Dhabi Urban Planning council, 2010) and Jordanian Green Building Guide in Jordan (Ministry of Public Works and Housing, 2013), all are examples of localised GBCs.

Most of these codes are voluntary rather than mandatory and are designed to objectively evaluate the performance of buildings regarding thermal comfort, acoustic, lighting, ventilation, water and energy efficiency. However, occupant physical and psychological satisfaction and health are not explicitly considered in such codes.

Globally, delivering “green” office buildings gained higher attention (WGBC, 2016). Organizations’ owners and decision-makers have recognized the potential benefits on investment via increased employee satisfaction and work performance when committing to green office buildings (Kats *et al.*, 2003). This is because the employees’ cost (i.e., salaries and benefits) is around 90% of the business cost, so even 1% improvement in employees’ work performance may contribute to substantial financial implications for the organization (WGBC, 2014).

However, it is still unclear whether green office buildings perform as promised in terms of the quality of the indoor environment. In particular, research suggests that many high-level green-certified buildings in the USA, the UK, and elsewhere fail in delivering effective performance in improving IEQ (Veitch *et al.*, 2007; Fostervold and Nersveen, 2008; Altomonte and Schiavon, 2013; Gou, Prasad and Lau, 2013; Ravindu *et al.*, 2015; Tham, Wargocki and Tan, 2015; Sediso and Lee, 2016). In many instances, green office buildings may show unintended consequences, including reduce occupants’ comfort and satisfaction or increase the prevalence of sick building syndrome symptoms, which may increase the absenteeism and presenteeism rate, and in return could negatively influence the work performance of employees.

In green buildings, the performance gap can be categorised into three classes, namely energy efficiency, quality of the indoor environment, and occupant perception (Jain *et al.*, 2020). Since the energy performance alone cannot capture the full impact of green building on its occupants, and the energy efficiency gap is beyond this thesis interest, hence, my research focuses on the two gaps (i.e., IEQ performance and occupant perception). IEQ aspect can be defined as the quality of a building’s environment in relation to the health and wellbeing of its users (CDC, 2020). It comprises mainly of four parameters, Indoor Air Quality (IAQ) and thermal, visual and acoustic comfort (ISO 17772-1, 2017).

Although the performance gap in the IEQ in green buildings was examined by a good amount of research around the world (Gou, Lau and Shen, 2012; Altomonte and Schiavon, 2013; Ravindu *et al.*, 2015; Altomonte, Saadouni and Schiavon, 2016;

MacNaughton *et al.*, 2017), the evidence of the in-use performance of green buildings does not exist in the ME. To date, no previous study has evaluated the performance of IEQ in green buildings, thus understanding how occupants perceive their buildings is still an unsolved challenge. Also, the actual role of the used localised GBCs in improving the performance of the IEQ and increase occupant comfort and health has not been investigated in this region. Missing the opportunity of incorporating occupants' feedback into the future green buildings' development.

The quality of the indoor environment and its influence on occupants has become one of the worrying concerns we face today. Particularly, in light of the current health crisis, i.e., COVID-19 epidemic, since the majority of people spend most of their time indoors, and improper IEQ could lead to several health problems, i.e., sick building syndrome symptoms. It is becoming extremely important to ensure that GBCs not only embrace environmental issues but also provide a high-quality indoor environment for people.

1.2 Research problem

Much uncertainty still exists about the actual performance of the IEQ in green office buildings, and the potential impacts of IEQ on employee satisfaction, health, and work performance. The research problem can be classified into three categories as following:

1.2.1 Green Building Codes

Although many emerging international policies like ISO 52003 (EN ISO 52003-1, 2017), Kyoto Protocol (UNFCCC, 1998), and Energy Performance of Buildings Directive in the European Union (European Parliament, 2010) have emphasised the importance of attaining a balance between saving energy and delivering proper IEQ, historically, due to the climate change challenges, energy and carbon aspects have gained higher attention, this has resulted in devaluation the IEQ aspect.

Most of GBCs worldwide have incorporated the IEQ as an aspect to evaluate the "greenness" level of buildings. However, in most GBCs, specifically the localised codes, IEQ has been given less credit weight compared to other green building design aspects, such as energy efficiency (Table 1.1**Error! Reference source not found.**). For example, the international LEED standard has weighted the IEQ by 14% compared to 32% for energy efficiency, and in the localised JGBG, IEQ is given the lowest credit weight of (9%) compared to other green design aspects.

Moreover, most of the identified requirements in GBCs focus on the objective assessment of IEQ metrics (e.g., IAQ, lighting, acoustic, thermal conditions), which is usually required to be conducted within the first two months of obtaining the green certification, that does not consider the occupancy conditions (USGBC, 2019). However, occupants' related aspects, such as health, physical, and psychological comfort are neglected in most of GBCs, rising a question if GBCs are really doing enough in terms of enhancing occupant satisfaction, health, and work performance.

Table 1.1 The relative weighting of energy efficiency (EE) and indoor environment quality (IEQ) in two global GBCs and five localised GBCs in the ME.

			Relative Weighting (%)	
Country	Green Building Code	Version date	EE	IEQ
United States	Leadership in Energy and Environmental Design (LEED)	2007	32%	14%
United Kingdom	Building Research Establishment Environmental Assessment Method (BREEAM)	2018	19%	15%
Jordan	Jordanian Green Building Guide (JGBG)	2013	39%	9%
Qatar	Global Sustainability Assessment System (GSAS)	2009	72%	42%
United Arab Emirates	Pearl Building Rating System (PBRS)	2007	44%	37%
Israel	Israeli Green building Standard (SI 528)	2005	40%	18%
Egypt	Green Pyramid Rating System (GPRS)	2011	25%	10%

1.2.2 Performance gap

Achieving a balance between the high level of building energy performance and satisfying quality of indoor environment could be a challenge for building designers, specifically, in green buildings, which are originally developed from the need for more energy-efficient and environmentally buildings.

However, improving the energy performance of green office buildings can curtail the occupant comfort and health. Especially in hot climate regions, such as the ME, where the office buildings are designed with an airtight envelop, no operable windows, and fully control HVAC systems. The majority of occupants in these buildings have limited control over indoor environmental conditions (e.g., temperature, light), so saving more energy. Such conditions can negatively influence occupant satisfaction with IEQ and cause profound health consequences.

Researchers around the world have observed a significant performance gap in green buildings (Gou, Lau and Shen, 2012; Altomonte and Schiavon, 2013; Alborz and Berardi, 2015; Ravindu *et al.*, 2015; MacNaughton *et al.*, 2017). This gap is defined as the difference between the predicted performance of IEQ during the design stage and that measured performance during the operation stage (Figure 1.1). The most two debated IEQ aspects in the literature over the past two decades were thermal comfort and IAQ (Liang *et al.*, 2014; Tham, Wargocki and Tan, 2015; Sediso and Lee, 2016), this could be referred to the less attention has given to these two aspects in GBCs.

Most of the conducted research all over the world has followed a single methodological approach of Post Occupancy Evaluation (POE) to evaluate the IEQ in green buildings, which is relying on the objective assessment of IEQ metrics (Leaman and Bordass, 2007a; Paul and Taylor, 2008; Brown *et al.*, 2010; Thatcher and Milner, 2012, 2016; Altomonte and Schiavon, 2013; Gou, Prasad and Lau, 2014; Sediso and Lee, 2016). However, to understand how the green building is performing against the design intents required a systematic and continuous evaluation covering building itself and its occupants.

Further, although the international POE of green buildings is growing rapidly, little is known about the as-built performance of green buildings in the ME. So far it is not clear, whether the IEQ in such buildings meets the expected performance by designers, and if so, whether the occupants are satisfied with their indoor environment quality.

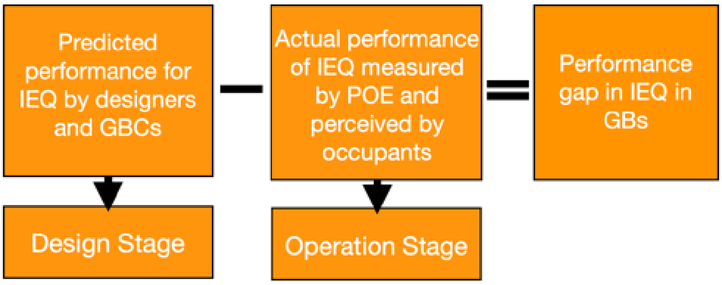

Figure 1.1 The performance gap of IEQ in green buildings.

1.2.3 Thermal comfort codes and energy use

In the absence of local thermal comfort standards in the ME, the international ASHRAE 55 standard (ANSI/ASHRAE 55, 2017) and/or Fanger's Predicted Mean Vote (PMV) (Fanger, 1970) are used to design the indoor thermal environment in air-conditioned buildings. These standards also are adopted by the localised GBCs in this region to identify the acceptable thermal comfort ranges in green buildings.

However, such standards have no basis of empirical data from this region, and they do not consider several factors such as physiological, contextual, and occupant psychological acclimatization (Indraganti and Boussaa, 2017). Such factors may affect people concept of coolness and warmness.

Research has questioned the applicability of the applied international standards in predicting the occupant thermal sensation in hot climates (Indraganti *et al.*, 2014). It has been argued that there is an inconsistency between the predicted thermal comfort levels and the observed occupant thermal sensations, which end up with an “overcooling” in air-conditioned buildings. This may lead to higher electricity consumption for space cooling and lower thermal comfort accompanied by cold state tendency between occupants (Al-ajmi, 2010; Indraganti and Boussaa, 2017).

In the ME, which is one of the world’s hotter regions, the current cooling energy demand represents 70% of the total building energy demand (Nematollahi *et al.*, 2016). This percentage is projected to double by 2100 (IEA, 2018), as a result of climate change and the continued growth of the population. Hence, there is an urgent need to ensure that the current applied thermal comfort standards in this region are avoiding the “overcooling” and assist in improving energy efficiency without compromising occupants’ thermal comfort.

1.3 Research scope

The quality of the indoor environment and its impact on building’s occupants is a complex issue. To retain focus, this thesis deals only with IEQ in two types of office buildings: (i) green buildings designed and certified to localised (i.e., JGBG) and international (i.e., LEED) GBCs. (ii) Conventional buildings, that are built according to the national building and construction codes, with no green design intention.

In addition, the focus of this thesis is on full-time employees working in the surveyed buildings, because they spend up to 8 hours daily inside their offices, and the quality of indoor work environment could significantly affect their comfort, health, and work performance.

Further, this thesis focuses on two measurable IEQ aspects, i.e., IAQ and thermal comfort, as evidence showed that these aspects can have a direct influence on occupant health and work performance (Wargocki *et al.*, 1999; Nakano J, S and K, 2002; Lan and Lian, 2009). These two aspects also are the most debated in the green building literature. Though, other

IEQ aspects, i.e., visual and acoustic comfort are beyond our objective assessment, as they were broadly seen as satisfactory by occupants who were surveyed in green buildings in several studies around the world. Our subjective assessment for occupant perception covered all IEQ aspects (i.e., IAQ, thermal, visual and acoustic comfort), and other secondary IEQ metrics (i.e., privacy, biophilia, odour), as they could have indirect effects on occupant comfort and health (WGBC, 2016).

The ME is selected to be the context of this study and to answer the three research questions illustrated in the following section (1.4) for two reasons:

(i) The number of green buildings in the ME is increasing considerably, these buildings are certified under a wide range of GBCs. However, to date, no study has examined the as-built performance of green buildings in this region.

(ii) The body of evidence of the actual role of localised GBCs in improving occupant satisfaction, thermal comfort, and perceived health is not existing in the ME, thus, there is an urgent need to increase the POE database of green-certified buildings in this region.

1.4 Aim and objectives

This research aims to investigate whether green office buildings in the Middle East meet the requirements of thermal comfort and IAQ that specified by GBCs, and if so, to what extent they are improving the occupants 'satisfaction, perceived health and work performance compared to the occupants in conventional buildings. This aim is achieved by addressing three research gaps identified in section 1.2, which are translated into three key research questions that are presented with objectives and the applied research methods as followings:

Research Question 1 What is the actual role of localised GBCs in improving the performance of IEQ, occupant satisfaction, thermal comfort, and perceived health?

Objective 1-A To objectively assess the IEQ (thermal conditions and IAQ) experienced by occupants of the JGBG-certified building against those experienced by them in their previous conventional buildings.

Objective 1-B To investigate if moving from conventional buildings to a JGBG-certified building has a positive impact on occupant satisfaction with IEQ, thermal comfort, and prevalence of SBS symptoms.

Research Methods Data were collected through a longitudinal field study with repeated measures protocol (over 12-month). We follow 120 employees as they transitioned from four conventional buildings to a single office building certified under the localised JGBG in Jordan. Objective and subjective measurements were conducted pre- and post-moving to the green building (Covered in Chapter 2).

Research Question 2 To what extent LEED office buildings in the ME achieve the specified minimum IEQ standards, after handover, and to what extent occupants of these buildings are satisfied and demonstrate better work performance compared to occupants in conventional buildings?

Objective 2-A To compare between design estimations and actual performance of IAQ and thermal comfort in LEED-certified buildings in occupancy stage. Taking LEED buildings in Jordan as a relevant example of LEED buildings in the ME.

Objective 2-B To compare between occupants in LEED buildings and conventional buildings in terms of their satisfaction of IEQ and work performance, which is measured through assessing absenteeism and presenteeism rates.

Research Methods Data were collected through POE, including objective assessment of thermal conditions and indoor CO_2 levels in 13 office buildings (5 LEED buildings + 8 conventional buildings) over summer and winter between 2017 – 2019. Also, we surveyed 502 full-time employees working in these buildings to compare satisfaction level of IEQ and work performance between building types. To better understand the context, this was supported by in-depth interviews to collect further information on the investigated buildings (Covered in Chapter 3).

Research Question 3 How suitable are international thermal comfort standards “including GBCs” for occupants in air-conditioned buildings in the ME?

Objective 3-A To investigate whether air-conditioned buildings (i.e., green and non-green buildings) in the ME, fall within the standards specified ranges of thermal comfort, and when they do, to what extent they are found to be thermally comfortable by their occupants.

Objective 3-B To calculate the difference between predicted and observed neutral (comfort) temperatures and estimate any potential reduction in the building energy use for space cooling based on this difference.

Research Methods Data were collected using two approaches, a meta-analysis of prior thermal comfort evidence in the ME and new thermal comfort field studies during summer and winter between 2017 and 2019. The objective measures covered 31 air-conditioned buildings within four countries. Also, the subjective measures cover 1,101 occupants in four occupancy types. This was followed by calculating the comfort temperature and energy model simulations for the investigated countries to compute prospect energy saving from space cooling (Covered in Chapter 4).

1.5 Thesis structure

This thesis consists of peer-reviewed journal publications, which represent the main contributions of this research presented in chapters 2, 3, and 4. Similarly, supporting work published in international conferences is included in 0 and 0. The content of these chapters is identical to the original published manuscript with minor style changes to deliver a consistent presentation. Each paper stands alone, including its introduction, literature review, and methodology, also, a preamble and a postscript link each chapter within the overall aim and narrative of the thesis.

Chapter 1- (this chapter) presents the research background and the research gaps, which are the motivation for the study of IEQ in green office buildings and its impact on occupant satisfaction, health and work performance. After, it establishes the aim and objectives of the thesis, also the scope for studies presented here.

Chapter 2- presents the first published journal paper to be submitted as part of this research. It is a within-subjects' comparison study. Results from this chapter led us to question the performance of IEQ in green office buildings, which designed to the international GBCs. Hence, we expand our investigation to include LEED-certified buildings, which is done in the following chapter.

Chapter 3- presents the second published journal paper. It is a systematic evaluation of the performance of IEQ in LEED-certified buildings in Jordan. It is a between-subjects comparison study. Results from this chapter highlight a clear problem in terms of occupant thermal comfort in air-conditioned buildings in hot climate region. This leads to conduct the following investigation.

Chapter 4- presents the third published journal paper, it is a large-scale thermal comfort research. This chapter examines the suitability of the applied thermal comfort codes for the occupant in air-conditioned buildings in the ME. It provides an empirical evidence of thermal comfort gap in air-conditioned buildings in the ME.

Chapter 5- concludes all studies by summarising the main outcomes regarding the aim and objectives of the thesis, and identifies the key research contribution of the work, then recommends future research areas.

0- presents the first published conference paper. It examines the role played by green certification and gender differences in the prevalence of self-reported SBS symptoms. This study supports Chapter 3 and showed how green certification failed in reducing the prevalence of self-reported SBS symptoms.

0- presents the second published conference paper. It systematically compares the performance of the localised JGBG and the imported LEED in terms of IAQ and reported absenteeism rate. This study is in a line with the work presented in Chapter 2.

1.6 Publications associated with this research

The research presented in this thesis is published and accepted in peer-reviewed journals and presented in international conferences, also the research dataset of each paper has been published. The research dissemination as follows:

1.6.1 Peer reviewed paper

R. Elnaklah, I. Walker, S. Natarajan, Moving to a green building: Indoor environment quality, thermal comfort and health, Building and Environment. 191 (2021) 107592. https://doi.org/10.1016/j.buildenv.2021.107592 (Chapter 2).

R. Elnaklah, D. Fosas, S. Natarajan, Indoor environment quality and work performance in "green" office buildings in the Middle East, Building Simulation. 13 (2020) 1043–1062. https://doi.org/10.1007/s12273-020-0695-1 (Chapter 3).

R. Elnaklah, A. Alnuaimi, B. Alotaibi, E. Topriska, I. Walker, S. Natarajan, Thermal comfort standards in the Middle East: current and future challenges, Buildings and Environment. 200 (2021) 107899. https://doi.org/10.1016/j.buildenv.2021.107899 (Chapter 4).

1.6.2 Proceeding of international conferences

R. Elnaklah, D. Fosas, Sukumar Natarajan, Are Green Buildings Doing Enough? The role of green certification and gender on sick building syndrome, in: PLEA (Planning Post Carbon Cities), Coruña, Spain, 2020: pp. 193–198. https://doi.org/https://doi.org/10.17979/spudc/9788497497947 (Appendix A).

R.A. Elnaklah, S. Natarajan, A comparison of indoor air quality and employee absenteeism in 'local' and 'imported' green building standards, in: Indoor Air Quality, Ventilation and Energy Conservation in Buildings, Bari, Italy, 2019: pp. 42–89. https://doi.org/10.1088/1757-899X/609/4/042089 (Appendix B).

1.6.3 Datasets

R. Elnaklah, S. Natarajan, Dataset for journal article "'Moving to a green building: indoor environmental quality, thermal comfort and health,'" University of Bath Research Data Archive, Bath, 2020. https://doi.org/https://doi.org/10.15125/BATH-00925.

R. Elnaklah, Dataset for "'Indoor environment quality and work performance in "green" office buildings in the Middle East,'" University of Bath Research Data Archive, Bath, 2020. https://doi.org/https://doi.org/10.15125/BATH-00863.

R. Elnaklah, A. Alnuaimi, B. Alotaibi, E. Topriska, S. Natarajan, Dataset for "'Thermal comfort standards in the Middle East: current and future challenges,'" University of Bath Research Data Archive, Bath, 2021. https://doi.org/10.15125/BATH-00967.

1.6.4 Awards and scholarships

2020- SBSE scholarship in 35th PLEA conference: Planing Post Carbon Cities (Scholarship for the top 30 PhD research), provided by the Society of Building Science Educators.

2019- Project prize for 'Portable lab', in the third Santander Technology Fund round, provided by Santander Bank.

2017-2021- Architecture and design, Al-Ahliyya Amman University scholarship to carry research as a PhD student.

2 Moving to a green building: indoor environment quality, thermal comfort, and health

2.1 Preamble

IEQ of green buildings is an aspect largely debated, yet evidence indicates that there is a gap in the performance of IEQ and occupant's perception and health in green buildings. This chapter provides the results of our longitudinal field study that examines whether localised GBCs improve building performance, occupant satisfaction and perceived health. The localised JGBG in Jordan was selected to be examined as an example of other emerging localised GBCs, due to three reasons:

1- Developing world including the Middle Eastern countries have produced their localised codes for green building design, which often do not systematically recognise IEQ or health as crucial issues, while the main attention has paid to other green design aspects (e.g., energy and water efficiency), which is seen in the JGBG.

2- In countries with limited energy and water sources such as Jordan, the most considered performance metrics in evaluating green building is how much the building achieves the energy or water-saving targets, while the important impact of IEQ on occupant comfort and health is mostly ignored. To date, there is no study examining the role of localised GBCs in improving the IEQ performance and occupant experience, whether on a theoretical basis or from a performance standpoint.

3- The case study of green building investigated in this chapter provided us with the opportunity to follow a novel approach on several fronts, including longitudinal research design with repeated measures within subjects. We follow the same employees of a single organisation as they transition from old conventional buildings to the first JGBG-certified building. We repeated the objective and subjective assessments three times over one year (pre- and post-moving), then we compare results to quantify the magnitude of improvement. The repeated measures protocol is a well-established method for controlling participant variability between pre- and post-conditions, where the results can be considered more rigorous.

2.2 Declaration of authorship

This declaration concerns the article entitled:
Moving to a green building: indoor environment quality, thermal comfort, and health
Publication status (tick one)
Submitted ☐ In review ☐ Accepted ☐ Published ☑
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• Formulation of ideas: R. Elnaklah (80%) and S. Natarajan (20%). • Design of Methodology: R. Elnaklah (80%) and S. Natarajan (20%). • Data Collection: R. Elnaklah (100%). • Data Analysis: R. Elnaklah (80%), S. Natarajan (10%).and I. Walker (10%). • Presentation of data in journal format: R. Elnaklah (80%) and S. Natarajan (20%).
Statement from Candidate
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.
Signed: Rana Elnaklah **Date:** 17th Jan 2021

2.3 Abstract

A global movement towards the creation of “green” buildings is currently underway. Although driven primarily by an external environmental agenda such as energy or carbon, there is growing recognition that greener buildings could affect the Indoor Environment Quality (IEQ). However, localised green building codes, especially in the developing world, often do not systematically recognise IEQ or health as crucial issues, which therefore remain understudied. Since the developing world alone is expected to nearly double current global built floor space by 2050, it is crucial that green buildings perform holistically to be effective. Here, we follow 120 employees of a single organisation as they transition from four conventional office buildings to the first green building (GB), designed to the local Jordanian Green Building Guide. We ask if the move has a positive effect on occupant perception of IEQ, thermal comfort and prevalence of Sick Building Syndrome (SBS), using a repeated-measures protocol. Statistically significant differences in thermal conditions, positively biased towards the GB, were observed across the move, and this enhanced occupant thermal comfort. Surprisingly, no significant improvement in occupant perception of air quality, visual and acoustic comfort was detected after moving to the GB, while odour, mental concentration, and glare were perceived to be poor in the GB and associated with an increase in the prevalence of SBS symptoms. Hence, our results support the growing concern that green buildings may create unintended consequences in terms of occupant comfort and health in the pursuit of a better thermal environment and energy efficiency.

2.4 Introduction

Much of the future growth in the construction of new buildings is expected to come from the developing world. For example, if we take the Global South to include China, India, Africa, the Middle East, and Latin America, then the expected additional built floor space by 2050 from these regions is 171 billion m^2; 100 billion m^2 of which will be in countries with no building energy regulations at the present (IEA, 2013). This additional growth is equivalent to 75% of the current global total of 230 billion m^2 (IEA, 2017). Recognition of this has driven a significant rise in Green Building Codes (GBCs) and regulations to drive down energy consumption from buildings (Janda, 2009).

Countries in the Global South including the Middle East have developed local GBCs designed to suit the specific local needs of each region, such as the Pearl Building Rating

System (PBRS) in the United Arab Emirates (Abu Dhabi Urban Planning council, 2010), the Global Sustainability Assessment System (GSAS) in Qatar (Gulf Organization for research and developmnet (GORD), 2020), and the Jordanian Green Building Guide (JGBG) in Jordan (Ministry of Public Works and Housing, 2013). Most of these codes were adapted from well-established international standards (e.g., ASHRAE 55 (ANSI/ASHRAE 55, 2017), ASHRAE 62.1 (ANSI/ASHRAE 62.1, 2010)) or global green building certification schemes, such as BREEAM from the United Kingdom (BREEAM, 2019) and LEED in the United States (USGBC, 2019). While these GBCs should help reduce building consumption, and so are a necessary forward-looking step, it is important at the same time to be vigilant for unintended side-effects arising from the move to greener buildings (The European Parliament and the Council of the European Union, 2018). Interest in the performance of green office buildings, in particular, has increased dramatically over the past two decades (WGBC, 2016).

From a business perspective, it has been argued that a green office building not only reduces energy consumption but also improves the Indoor Environment Quality (IEQ) (Ries *et al.*, 2006; Gou, Prasad and Lau, 2014). This is interpreted as resulting in more comfortable, satisfied, and productive employees with reduced sick leave, and hence higher economic returns (Fisk and Rosenfeld, 1997; Tham, 2004; Ries *et al.*, 2006). However, a green or energy-efficient office building per se does not guarantee a healthy indoor environment for employees. Indeed, green buildings are known to be particularly susceptible to unintended consequences that negatively affect the IEQ of workplaces and in some cases might result in "Sick Building Syndrome" (SBS)[1] (Davies and Oreszczyn, 2012). Given that people spend around 90% of their time indoors in industrialised economies, a trend towards which developing economies are likely to move, it is essential that improvements in overall building efficiency are not accompanied with poor IEQ (The European Parliament and the Council of the European Union, 2018).

2.4.1 Jordanian Green Building Guide (JGBG)

In Jordan, the JGBG was produced in 2013 to gradually replace the international LEED standard. JGBG is used to evaluate the performance of buildings in terms of six major aspects: IEQ, Building management, Site selection, Material, Water and Energy efficiency (Elnaklah and Natarajan, 2019). JGBG certified buildings into four categories

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[1] SBS is defined as a medical condition where the occupant of a building suffer from symptoms of illness or feel unwell for no apparent reason, these symptoms can be linked to time spent in the building (Passarelli, 2009).

(A, B, C, and D) based on the obtained credits. Although the JGBG scheme is based on LEED, it was designed to reflect the local Jordanian context. For example, JGBG pays great attention to energy and water efficiency, as they are considered the two main challenges for Jordan. It would seem that the focus on the more immediate issues of energy and water has resulted in the relative devaluation of IEQ, Figure 2.1 (Left) (Ministry of Public Works and Housing, 2013).

In JGBG, IEQ is evaluated based on evaluation the performance of ten metrics that focus on Indoor Air Quality (IAQ), ventilation, acoustics, lighting, thermal comfort, and the innovation design of IEQ, Figure 2.1 (Right). However, eight out of ten items are elective and not considered essential areas in the overall green evaluation process, particularly for thermal comfort and ventilation aspects, that lack any compulsory specifications. A building can be certified with the highest green category ‘A’ when it achieves 80% of the total assigning credits, and this can be easily attained with covering the minimum requirements of IEQ items.

Further, the occupants’ health, physical and psychological aspects are not explicitly addressed in the JGBG, thus little is known about the real-world performance of IEQ of certified buildings under local GBCs in Jordan and the wider Middle East. Given the current health crisis prompted by the COVID-19 pandemic, where poor IEQ is associated with the potential for increased spread of pathogens, combined with the expectation of longer indoor occupancy periods in the future, there is a need to ensure that GBCs not only assist in reducing building energy or water consumption but also provide a high-quality indoor environment for users as they promised.

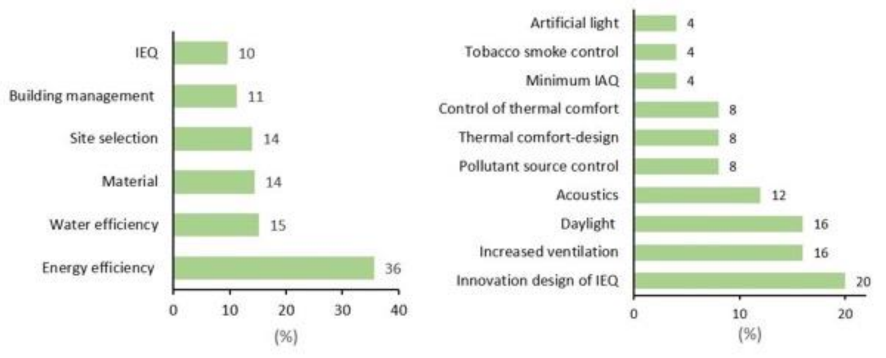

Figure 2.1 The Relative weighting of the individual parameters in the Jordanian Green Building Guide in Jordan (Left), the relative weighting of the ten metrics of IEQ specified by the JGBG (Right) (Ministry of Public Works and Housing, 2013), totals for all bars in each plot sum to 100%.

2.4.2 Research objectives

This paper aims to examine whether localised GBCs improve building performance, occupant satisfaction and health compared to conventional buildings. We address this aim using the JGBG in Jordan as a case study, with the following objectives:

1. To assess the IEQ (thermal conditions and indoor air quality) experienced by occupants of the first – and only – JGBG-certified office building against those experienced by them in their previous conventional office buildings.
2. To investigate if moving from conventional office buildings to a green-certified office building has a positive effect on the perceived comfort of IEQ, perceived health and the environmental attitude of occupant.

2.5 Current literature

The role of GBCs in improving the performance of IEQ and its effect on employee satisfaction and health have become a primary concern. There is a good amount of empirical research investigating the IEQ of green office buildings certified under international codes (e.g., LEED, BREEAM) or localised codes, such as ‘EEWH’ in Taiwan, ‘Green Mark’ in Singapore, and ‘Green Star SA’ in South Africa, summarised in Table 2.1.

Seven out of sixteen studies in Table 2.1 have assessed BREEAM buildings in the UK (Altomonte, Saadouni and Schiavon, 2016), LEED buildings in USA (Altomonte and

Schiavon, 2013; Alborz and Berardi, 2015; MacNaughton *et al.*, 2017) and in other countries that imported LEED, such as Sri Lanka (Ravindu *et al.*, 2015), Hong Kong (Gou, Lau and Shen, 2012), and Jordan (Elnaklah, Fosas and Natarajan, 2020). It is somewhat surprising that no improvement in occupant satisfaction of IEQ was reported in all these studies except one (MacNaughton *et al.*, 2017). The observed results were either lower satisfaction in all or some of IEQ metrics (Ravindu *et al.*, 2015; Elnaklah, Fosas and Natarajan, 2020) or no significant differences were reported in employee satisfaction between green buildings and conventional buildings (Gou, Lau and Shen, 2012; Altomonte and Schiavon, 2013).

On the other hand, seven out of nine studies (Thomas, 2010; Liang *et al.*, 2014; Pei *et al.*, 2015; Tham, Wargocki and Tan, 2015; Sediso and Lee, 2016; Thatcher and Milner, 2016; Liu *et al.*, 2018), that assessed the performance of certified buildings under localised GBCs observed improved satisfaction, wellbeing, perceived air quality, and self-reported productivity in the green buildings compared to conventional buildings (two had lower (Thatcher and Milner, 2012; Menadue, Soebarto and Williamson, 2014), whereas one did not have a comparator (Thomas, 2010)). If we assume a direct relationship between perception and performance, these results suggest that buildings under localised GBCs outperform buildings with international green building certification in terms of IEQ, when they are compared to conventional buildings.

In the Middle East, there are approximately 1,200 green-certified buildings built to a range of global and localised GBCs, of which 28 are in Jordan (Ministry of Public Works and Housing, 2013; Sabbagh, Mansour and Banawi, 2019). A survey of the literature demonstrates that little is known about the as-built performance of these green codes, with only one study investigating the IEQ performance of LEED buildings in this region done by the authors (Elnaklah, Fosas and Natarajan, 2020), and one study undertaking energy performance monitoring (Rosenlund, Emtairah and Visser, 2010).

Instead, current literature in the Middle East has focused primarily on theoretical analyses of the benefits or applicability of green buildings mostly for new-build (Alrashed and Asif, 2012; Attia and Al-Khuraissat, 2016; Ibrahim, 2017) but also in terms of retrofits (Krarti and Dubey, 2018). Some studies have also examined the applicability of international GBCs in the region (Attia and Abaieh, 2013; Awadh, 2017) including the broader links with sustainability and the United Nations Sustainable Development Goals (Alawneh *et al.*, 2019) and urban planning (Ferwati *et al.*, 2019). Remarkably, there is no study examining the role of localised GBCs in improving the IEQ and occupant experience in the region, whether on a theoretical basis or from a performance standpoint. Overall, however, it is clear that a study looking at IEQ in the Middle East region is both timely and necessary, to add to the growing body of evidence on the relative impact of IEQ between conventional and green buildings.

Table 2.1 Summary of research evaluated the performance of IEQ in localised GBCs in different countries. CB indicates conventional building and GB indicates certified-green building.

Study	GBC	Country	Buildings (n)		Responses (n)		IEQ evaluation method	Findings
International			GB	CB	GB	CB		
(Altomonte, Saadouni and Schiavon, 2016)	BREEAM	UK	2	2	111	91	Survey	Lower satisfaction
(Altomonte and Schiavon, 2013)	LEED	USA	65	79	10,129[b]	11,348	Survey	No difference
(Alborz and Berardi, 2015)	LEED	USA	4[c]	-	593[a]	-	Physical measures + survey	Lower satisfaction
(MacNaughton *et al.*, 2017)	LEED	USA	6	4	69	40	Physical measures + survey	Higher cognitive function and lower sick leave.
(Ravindu *et al.*, 2015)	LEED	Sri Lanka	1	1	70[a]	-	Physical measures + survey	Lower satisfaction in thermal comfort and ventilation
(Gou, Lau and Shen, 2012)	LEED	Hong Kong	2	1	99	117	Survey	No difference
(Elnaklah, Fosas and Natarajan, 2020)	LEED	Jordan	5	8	261	241	Physical measures + survey	Lower satisfaction
Localised								
(Thomas, 2010)	Green Star	Australia	1[c]	-	238[a]	-	Survey	Higher satisfaction
(Liang *et al.*, 2014)	EEWH	Taiwan	3	2	134	99	Physical measures + survey	Higher satisfaction
(Tham, Wargocki and Tan, 2015)	Green Mark	Singapore	1	1	32	33	Physical measures + survey	Higher satisfaction
(Pei *et al.*, 2015)	China's Green Building Labelling	Mainland of China	10	42	500	500	Physical measures + survey	Higher satisfaction
(Liu *et al.*, 2018)	Three-Star	Mainland of China	-	-	1,892	2,194	Online survey	Higher satisfaction
(Sediso and Lee, 2016)	KGBCC	R.O. Korea	2	2	222[a]	-	Survey	Higher satisfaction

(Thatcher and Milner, 2016)	Green Star SA	South Africa	3	2	211	69	Survey	Better wellbeing, productivity and perceived air quality
(Menadue, Soebarto and Williamson, 2014)	Green Star	Australia	4	4	600 [a]	-	Physical measures + survey	Lower satisfaction
(Thatcher and Milner, 2012)	Green Star SA	South Africa	1[c]	-	161	79	Survey	Lower perceived productivity, physical, and psychological wellbeing

Notes:
[a] Sample size per building type not provided.
[b] Refers to data contained within the Centre of the Built Environment (CBE) database at the University of California, Berkeley.
[c] Number of surveyed conventional building is not provided.

2.6 Materials and methods

Extant research on the quality of the indoor environment in green buildings falls into two classes of research design. One class of studies uses a between-subjects design, where simultaneous or near-simultaneous Post Occupancy Evaluations (POE) to compare green and conventional buildings is undertaken (Altomonte and Schiavon, 2013; Ravindu *et al.*, 2015; Altomonte, Saadouni and Schiavon, 2016). The main strength of this research design is its ability to capture aleatory variability, especially if done at scale, thus producing more generalizable results. However, a potential weakness of this design is that the buildings, organizations, job types, management strategies, and psychological work environment might be fundamentally different, raising questions of comparability in studies that use small samples.

The second class of studies is the repeated-measures design, where the comparison is between the same sample of occupants when moving from conventional to green buildings (Ries *et al.*, 2006; Thatcher and Milner, 2012, 2016). Such studies usually ask respondents to rate the IEQ conditions in the old 'non-green' offices and the new green offices, often after they have moved to the new building. Hence, although such studies provide clear control over differences in job types, organisational, cultural, and idiosyncrasies tied to particular respondents, and are thus suited to smaller-scale study, the results need to be interpreted with caution given the risk of memory bias or biases arising from nostalgia for the old building or a neophilic response to the new one.

Our study falls into the second class, i.e., a longitudinal research design with repeated measures. We follow the same occupants working in the same organisation, a commercial company in Jordan, as they move from four conventional office buildings to a single JGBG-certified "green" building. The repeated measures research design is a well-established method for controlling participant variability between pre- and post-conditions, where the results can be considered more rigorous (Miller, 1984). As the confounding variables of age, gender, job role, organisational differences, etc. are well-controlled, we expect a very sensitive measure of the effect of the building type on occupants (Charness, Gneezy and Kuhn, 2012). The data collection methods included five variables covered buildings and their occupants' performance (Elnaklah and Natarajan, 2020) (Table 2.2).

Table 2.2 The performance variables are evaluated in the conventional buildings and the certified-green building in this study.

Type	Aspect	Method	Metric
Objective	Building performance (Thermal conditions + IAQ)	Longitudinal measures + spot measures	Air temperature (T_a), Mean radiant temperature (T_r), Relative humidity (RH), Air speed (V_a), and indoor Carbon Dioxide concentration level (CO_2)
Subjective	Perceived comfort	Survey	Self-reported
	Thermal comfort	Survey + spot measures	Thermal Sensation Votes (TSV), Thermal Preference Votes (TPV), Predictive Mean Votes (PMV), Clothes thermal insulation (clo), and Metabolic rate (met)
	Perceived health	Survey	Frequency of symptoms of Sick Building Syndrome (SBS)
	Occupant environmental attitude	Survey	Self-reported

2.6.1 Study description

This study consists of two phases (Figure 2.2). Phase I (pre-moving, Jul - Nov 2017) involved surveying 120 employees with co-incident monitoring of the indoor environment parameters, spread over four medium-sized conventional office buildings. Phase II (post-moving), using identical survey and sensor instruments, was conducted in two waves. The first wave was between Jul - Nov 2018, six months after the employees transitioned to the new green building to capture early reactions to the move. The second wave was undertaken between Jan – Feb 2019, twelve months after transitioning to account for the fact that 90% of new buildings display poor control performance in the first year of operation and there is hence a period of "bedding in" (Yudelson and Meyer, 2013). All the buildings are located within a 1.5 km radius of each other in Amman, north-western Jordan, reducing logistical burden, and providing external climatic and environmental homogeneity. Gatekeeper consent (via the upper management), as well as prior informed consent from all participants were obtained. Ethical approval was obtained using the approved university procedures. The organisation, buildings, and participants have been anonymised for security and data privacy. Hence, we refer to the four conventional buildings as buildings CB1, CB2, CB3, and CB4, while the green building is referred to as building GB.

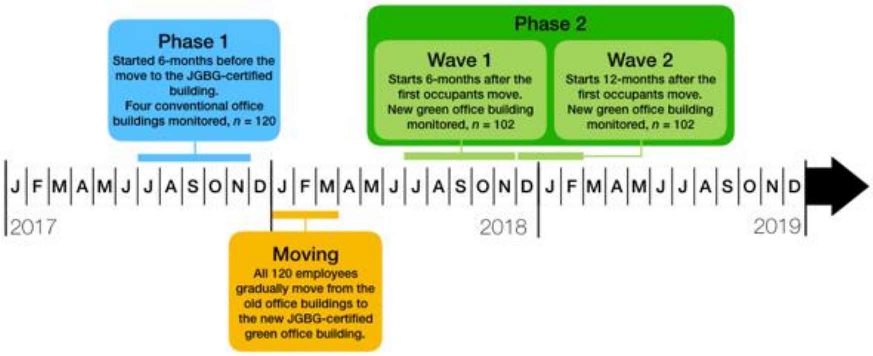

Figure 2.2 Research design timeline and data collection; $n\_CBs = 4; n\_GB = 1; n\_(occupants\ (CBs\ ) = 120; n\_(occupants\ (GB\ ) = 102$. Length of bars indicates months in which data were collected. All phases involved longitudinal and periodic cross-sectional data collection.

2.6.2 Buildings' description

Table 2.3 compares the buildings' attributes and key characteristics of the CBs and GB. All surveyed buildings in this study are office buildings (Figure 2.3). The CBs were owner occupied, except CB4 was multi-tenanted. CBs were constructed approximately 20 years ago and complied with the legislation and building regulation for the Municipality of Greater Amman at that time. All CBs have cellular (for single occupant) and shared (2 - 3 occupants) offices.

The green building under this investigation is the first building rated under the JGBG in Jordan, where it received the highest possible rating of 'A'. It is also LEED-Platinum certified. It was completed and occupied by January 2018. The majority of the building's layout is open with no partitions, with few numbers of cellular offices are occupied by the upper management staff. The GB achieved 67% and 72% of the IEQ requirements specified by the LEED and JGBG, respectively (Table 2.4).

In addition to passive design features, such as appropriate building orientation and window shading, the GB includes renewable generation in the form of facade-integrated 300 Wp monocrystalline photovoltaic panels with an efficiency of 20%. According to the elective requirement in JGBG, a computer energy modelling of the building was produced at the time of the design stage using e-QUEST software. The expected savings in energy consumption were 39% compared to the building energy baseline model. It is noteworthy, however, that there is some debate on the quality and reliability of results in energy modelling (Negendahl, 2015; Imam, Coley and Walker, 2017), so such predictions need to be viewed carefully.

Table 2.3 Description of the conventional office buildings (CB) and green office building (GB), * M.M refers to Mixed-Mode ventilation system, ** refers to low volatile organic compound.

Feature	CB1	CB2	CB3	CB4	GB
Occupants (n)	26	27	37	30	102
Building size (m^2)	750	2,000	550	600	8,642
No. of floors	3	2	2	1	10
Occupants have view to the exterior (%)	65	55	40	53	23
Lighting fixtures	Halogen incandescent	Fluorescent	Fluorescent	Fluorescent	High efficiency LED
Ventilation system*	M.M	M.M	M.M	M.M	Energy recovery ventilators
Heating and cooling	Wall split air-conditioner	Multi-split units	Wall split air-conditioner	Wall split air-conditioner	Variable refrigerant flow system (VRF)
Operable windows	✓	✓	✓	✓	
Control temperature	✓	✓	✓	✓	(Only operating manager)
Control lighting	✓	✓	✓	✓	(Occupancy sensor systems)
Low VOC interior finishes**					✓

Figure 2.3 (a and b) Examples of conventional office buildings in this study, (c) external photo of the GB showing BIPV panels, (d) view of the interior in the GB shows the open plan workplace, and (e) view of the interior in CB1 sows shared office.

Table 2.4 The fifteen metrics of IEQ were passed by the GB to be certified under LEED and JGBG, * indicates prerequisite that should be achieved before starting the green certification process, all items in the table are elective except the two noted items, note: other six IEQ items specified by LEED and JGBG were excluded from the table, as they were not achieved by the GB

Item	LEED	JGBG
Minimum indoor air quality*	✓	✓
Indoor CO_2 level less than 1,100 ppm	✓	✓
Environmental Tobacco smoke control*	✓	✓
Outdoor air delivery monitoring	✓	
Increased ventilation	✓	✓
Construction IAQ management plan-during construction	✓	
Construction IAQ management plan-before occupancy	✓	
Low emitting materials-adhesives and sealants	✓	
Low emitting materials-paints and coating	✓	
Indoor chemical and pollutant source control	✓	✓
Controllability of systems-lighting	✓	✓
Thermal comfort-design	✓	✓
Thermal comfort-verification	✓	
Artificial light		✓
Acoustics performance		✓

2.6.3 Physical measurements

To complement the survey (Section 2.6.4) and ensure representative coverage across the buildings, i.e., the CBs and GB, longitudinal objective sensor data for both thermal conditions and IAQ were needed at an adequate spatial resolution (see installation 2.6.3.1). There is a wide variety of sensing that has been employed in the literature covering several metrics, such as lighting (Fostervold and Nersveen, 2008), ventilation (Seppanen, Fisk and Mendell, 1999), and noise level (Banbury and Berry, 2005). However, the most common are indoor air temperature (T_a) and relative humidity (RH) for thermal conditions, and indoor (CO_2) concentration level for IAQ (Seppanen, Fisk and Mendell, 1999; Maula *et al.*, 2016; Vehviläinen *et al.*, 2016).

The CBs in our study have concurrent mixed-mode ventilation, which refers to a combination of natural ventilation from manually operable windows and mechanical ventilation system (Ackerly, Baker and Brager, 2011). The GB is fully mechanically heated, ventilated, and air-conditioned through air handling units with a fixed set point. Meaning that the indoor conditions would rarely change at a frequency higher than one hour. As it was convenient to do so, a highly conservative record frequency of five minutes was selected. The data were collected using rigorously tested and calibrated Raspberry-Pi based sensors (Figure 2.4 a & b), as they have proven suitable for longitudinal field studies (Lovett *et al.*, 2016; Vellei *et al.*, 2016).

These were assembled in two varieties: one device to monitor T_a and RH together and the second dedicated to CO_2 concentration levels. Given that SBS symptoms or other occupant performance-related effects, i.e. perceived comfort can take four weeks to manifest (Kessler, Petukhova and McInnes, 2007), and the need to minimise seasonal effects, the physical measures were conducted in CBs for five months between Jul – Nov 2017 (i.e., one month before the administration of the survey and continued for three months after). In the GB, physical measures continued for eight months between Jul 2017 and Feb 2019 to replicate the survey.

Further, we benchmark the longitudinal sensing using periodic cross-sectional "spot" measurements using ISO7726 (EN ISO 7726, 2001) and ISO7730 (ISO 7730, 2005) compliant equipment 'SWEMA' (SWEMA, 2020) (Figure 2.4. c). The cross-sectional measurements were undertaken three times over the study period (i.e., once in CBs and twice in the GB) (Figure 2.2). These had a two-fold purpose: (i) to enable verification of the longitudinal data for air temperature and relative humidity such that any persistent errors could be identified and (ii) obtain co-incident measurements of mean radiant temperature (T_r) and air speed (V_a), necessary for evaluating PMV. The measurement period was five minutes for each workstation: two minutes to account for the temperature sensor's time constant and three additional minutes to obtain a stable reading of the PMV. The technical specifications for used sensors and instruments are given in section (2.13. a).

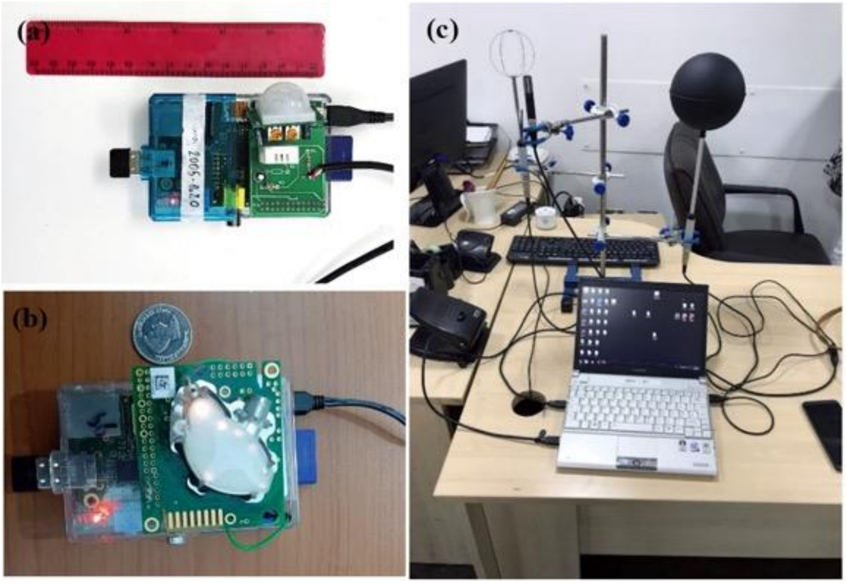

Figure 2.4 (a) The Raspberry-Pi based sensors (T_a + RH), (b) CO_2 sensor, and (c) SWEMA instrument position on employee's desk.

2.6.3.1 Sensor installation

In both building types, four factors were considered to calculate the required number of Raspberry-Pi based sensors for each building. Factors are namely, the net internal area, temperature differential, HVAC vents, and the employment density of full-time employees. This resulted in one sensor per 30 m^2 (Table 2.5). Sensor clock times were carefully set to ensure observations can be synchronised at analysis, as all sensors were set to offline logging mode. This was done to avoid the need for an internet-driven clock setting (e.g. in (Mogles *et al.*, 2017)), which is susceptible to clock errors if connectivity is lost. The installation of sensors was as following:

In the CBs (Phase I): the four office buildings were provided by 45 sensors, which were installed between Jul to Nov 2017. Sensors were located in both shared and private offices and were positioned on the employee's desk or in a safe place away from local sources of radiation (e.g., window, heater, PC monitor) at a height of 80 - 110 cm from the ground level to reduce the ambient ground temperature affecting the reading (Figure 2.5 a - d).

In the GB (Phase II): the building was provided with 38 sensors between Jul 2018 to Feb 2019. Sensors were distributed on the four floors and were located mainly in the open-plan area, as it represents the majority of the typical floor area, though some cellular offices were also monitored for completeness, the same criteria for positioning the sensors in CBs were followed in the GB (Figure 2.5 e & f).

Table 2.5 Installation of sensors in the monitored buildings , 'F' indicates the floor number within the building, sensor totals per building in bold.

Building	CB1			CB2			CB3			CB4	GB				
Floor	F1	F2		F1	F2		F1	F2		F1	F1	F2	F3	F4	
T_a + RH	2	8	**10**	2	6	**8**	4	4	**8**	**14**	10	10	10	2	**32**
CO_2	1	-	**1**	1	-	**1**	-	1	**1**	**2**	2	2	2	-	**6**

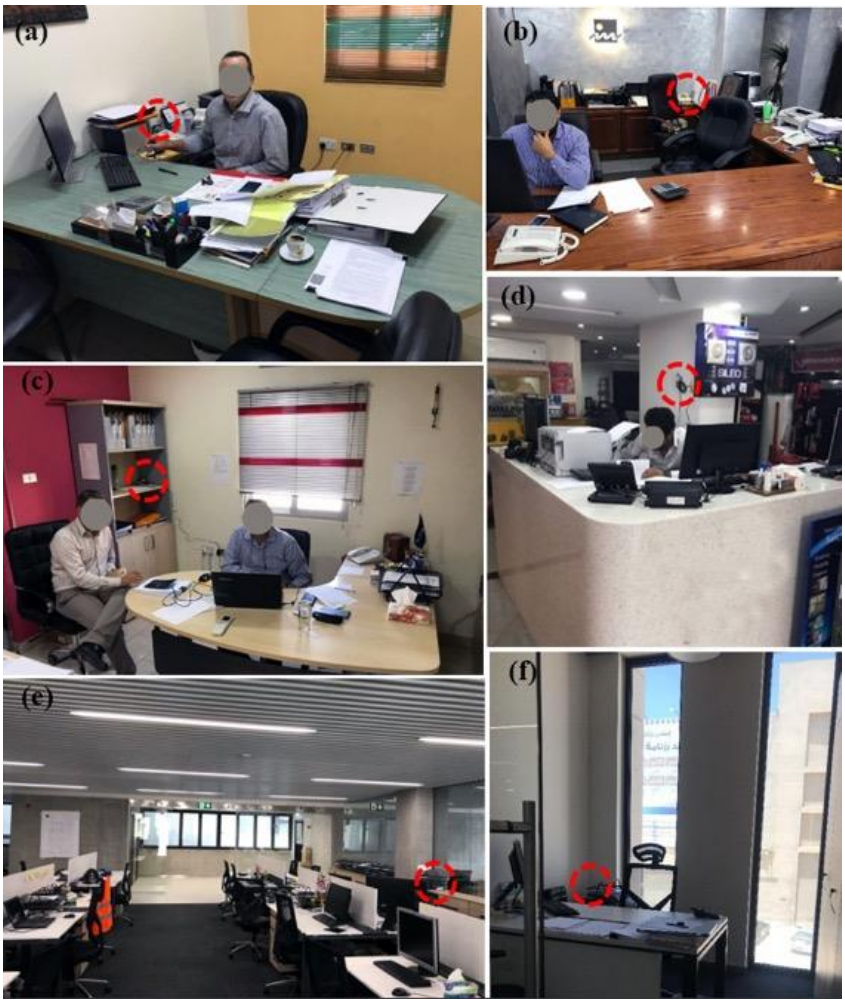

Figure 2.5 (a & b) Example of installation the T_a, RH, and CO_2 sensors on employee's desk in the CBs, (c & d) sensors positioned in a safe place at high 110 cm in CBs, (e) example of installation the sensors in the open plan area in the GB, and (f) example of installation the sensors in a cellular office in the GB.

2.6.4 Survey

To aid in comparison with other studies, our survey utilised existing survey instruments to cover the following four broad areas:

- Perceived comfort of IEQ was assessed using the World Green Building Council for Health, Well-Being, and Productivity in offices questionnaire (WGBC, 2014).

It consists of 13 questions on a 5-point satisfaction scale. The questions cover four main IEQ parameters namely IAQ, temperature, lighting, and acoustics, also four secondary metrics, including privacy, biophilia, odour, and view.

- Occupant thermal comfort was assessed using the widely used ASHRAE seven-point scale, which measures the TSV and TPV (ANSI/ASHRAE 55, 2017). The metabolic rate of participants was calculated using the standard tables provided by ASHRAE 55 and ISO 8996 (EN ISO 8996, 2004). As all buildings monitored in this study were used as offices and occupants were involved in typical office tasks (e.g., reading, writing, and computer typing), a light metabolic load of [1.00 - 1.30 met] was assumed throughout. Occupant clothing thermal insulation was assessed using ASHRAE 55 and ISO 9920 (EN ISO 9920, 2009) and ranged between [0.70, 1.00 clo] in summer in both building types, while in winter (GB only) it had a higher range of [1.09, 1.20 clo].
- Perceived health was evaluated by assessing the SBS symptoms. The Health and Work Performance Questionnaire produced by the World Health Organization (WHO HPQ) is used (Kessler, Petukhova and McInnes, 2007). The frequency of SBS symptoms was evaluated by asking the participants how much they were bothered by each of a group of ten medical symptoms (e.g., headache, irritated skin, itchy eyes, and other symptoms) in the 28-day preceding the survey date. The questions were on a 5-point response scale, ranged between 'not at all’, ‘a little of the time’, ‘some of the time’, ‘most of the time’, and ‘all of the time’.
- Occupant environment attitude was assessed using the Environmental Attitude Inventory (EAI) (Milfont and Duckitt, 2010), it consists of eight questions that measure the occupant tendency to be green.

Since most of the participants spoke Arabic as a first language, the survey questionnaire and consent form were translated into Arabic by a ‘sworn translator’ who has a high level of education and experience. The accuracy of the translation was verified as follows. The translated survey – without the English original – was sent to five university students fluent in both Arabic and English, and they were asked to translate it back to the English. Based on their suggestions, minor refinements, such as deletion of overlapping terms were made. The English originals were retained alongside the Arabic translations in the final questionnaire. The questionnaire was paper-based and distributed alongside a consent form to the employees in the selected buildings (section 2.13. b).

The surveys were administered in three rounds, the first was in the CBs (6-month pre-moving), the second and third rounds were in the GB (at 6 and 12-month post-moving, respectively). Participants were asked not to discuss their responses with anyone else. Average survey completion time was approximately five minutes. As the participants were tracked across the two phases of the study, each participant was identified using a unique identification code (ID), using the first two letters of the participant's forename followed by the first two letters of surname and month of birth (e.g., MA AL - 4).

2.6.4.1 Sample size

Initial sample size estimation for the paired samples *t*-test required for before-and-after comparison, assuming a medium effect size of d = 0.5 and power of 0.95, suggested a total sample size of 76 would be adequate in each phase of the experiment (Faul *et al.*, 2007). This minimum sample size was exceeded in this study, as the Phase I and Phase II sample sizes were 120 and 102 respectively. Over recruitment, in addition to improving the power of statistical tests, covers for study vulnerabilities, such as subject dropout or invalid survey responses. The overall demographic distribution was nearly identical in the two phases (section 2.13.c).

2.6.5 Analysis methods

As is customary in Jordan, weekdays were defined as Sunday to Thursday. Normal working hours were determined through management to be between 0900 and 1700 and this period was hence used to define working hours for analyses. The analysis was done using R (R Core Team, 2019), including packages from the 'tidyverse' family (Wickham *et al.*, 2019),'comf' (Schweiker *et al.*, 2019b), and 'cowplot' (Claus O. Wilke, 2020). The data analysis process was as follows:

- For the sensor data (where the response variable is numerical and continuous on a ratio scale as in the case of temperature (°C), relative humidity (%), air speed (ms^{-1}), and CO_2 concentration (ppm), we use Welch's heteroskedastic *t*-test to test the null hypothesis that there is no difference in the mean measurements between the two types of buildings. This is a common form of the *t*-test which assumes that samples follow a normal distribution, without assuming equal variance. Confidence intervals are reported together with the differences between groups. Here, effect sizes are reported using Cohen's well-known d metric, calculated using (Cohen, 1988):

$$d = (\mu a - \mu b)/s \tag{1}$$

where μa represents the sample mean in one group, μb the mean of the other group and s the pooled variance of the samples. Further, the objective measures from the GB are compared to the JGBG recommended ranges of thermal conditions and indoor CO_2 levels, which are based on ASHRAE 55 and ASHRAE 62.1 standards.

- For the survey data, each respondent provided a pair of scores, x_{CB} from Phase I and x_{GB} from Phase II[2]. Since we are interested in the consistent difference of participant outcomes (e.g. perceived comfort, perceived health) pre- and post-moving to the GB, the paired samples *t*-test was used due to its suitability for studies with repeated measures (Zimmerman, 1997). In comparing thermal comfort data, TSV was evaluated as "comfortable" within [-1 and +1] (ANSI/ASHRAE 55, 2017), whereas PMV was evaluated between [-0.5 and +0.5] (ISO 7730, 2005), as is common in studies of this kind (Indraganti and Boussaa, 2018). The paired samples *t*-test is once again used to compare the mean scores between the TSV and PMV in each phase of the study.
- The proportion of occupants who experienced any SBS symptom for 'some of the time' was calculated and compared to the ASHRAE 62.1 threshold of 20%, thus we can investigate whether buildings would classify as exhibiting SBS.

2.7 Results

Here we present the results of the objective data (building performance) and subjective data (perceived comfort, thermal comfort, and perceived health), and analysis using the methods presented in Section 2.6.5 above.

[2] The paired sample *t*-test requires "before" and "after" pairs of observations. In our case, we have "after" observations in two waves (6-month and 12-month after moving to the GB) (Figure 2.2). A comparison of data from both waves suggests no significant difference in occupant responses between the two waves (see section 2.13.d). We choose the second wave data as the "after" component of our pair as it commences 12-month into occupation when the majority of issues to do with commissioning and operating new buildings are likely to have been solved, as suggested in the literature (Yudelson and Meyer, 2013).

2.7.1 Building performance

Each building had its T_a, RH, and CO_2 measured 288 times per day for 149 days. Figure 2.6 presents density plots of the observed air temperature between 0900 and 1700 from the longitudinal monitoring during summer 2017 (Jul – Nov) in CBs, summer 2018 (Jul – Nov) and winter 2019 (Dec – Feb) in the GB. In the plots for summer, there is a clear downward trend in temperatures between July and November across both building types, but the gradient is much steeper in the mixed-mode CBs (~ 2.2 K per month) compared to the fully mechanically air-conditioned GB (~ 0.4 K per month). During the winter season, the mean air temperature in the GB was stable between December to February (cross-monthly mean = 20 °C, s = 1 °C).

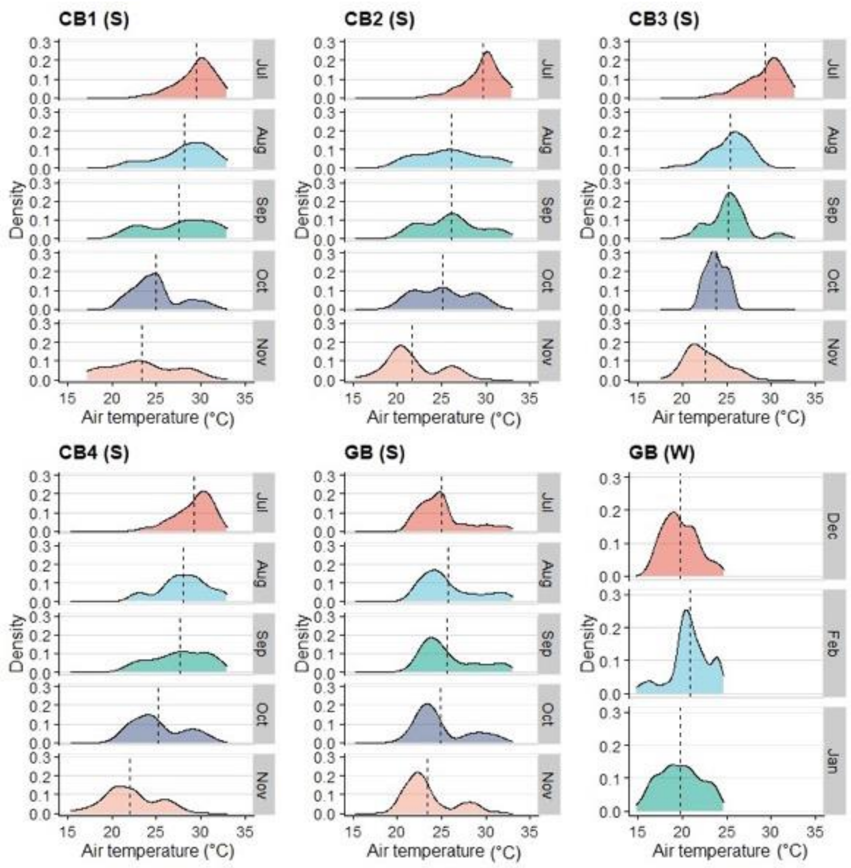

Figure 2.6 Monthly observed indoor air temperature distribution evaluated on working days between [0900 – 1700]. Summer (S) in the conventional buildings (CB) is over July – Nov 2017, whereas it is Jul – Nov 2018 for the green building (GB). Winter (W) data is only for the GB over Dec 2019 – Feb 2020, the dashed line represents the mean score for each month.

Figure 2.7 shows in boxplot the distribution of the T_a, RH, and CO_2 varied across monitored buildings during the same monitored period. Several effects are immediately apparent, for example, the GB is notably lower than the CBs in its mean daily T_a and RH measurements. Further, there were various sources of repeated sampling within the data. For example, each building had its T_a, RH and CO_2 recorded every day for five months, repeated over two years. To deal with the non-independence this introduces to the data, the analysis used linear mixed-effects models. The sole fixed-effects predictor was a binary variable coding whether each building was green or conventional. Month and a code representing each building's unique identity, were entered as random effects to see how much of the residual variance in the T_a, RH, and CO_2 measures could be explained by these identifiers once the effects of being a green building had already been accounted for.

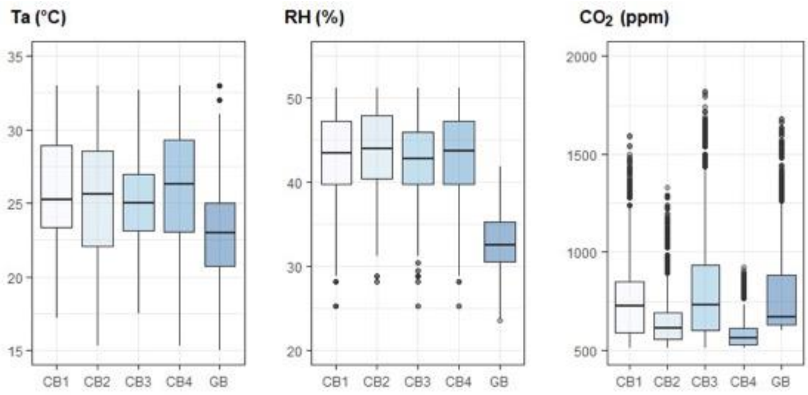

Figure 2.7 Box plots of the variation in air temperature (T_a), relative humidity (RH), and CO_2 across all monitored buildings using continuous measurement data between Jul 2017 and Feb 2019, (CB indicates conventional buildings and GB indicates green building), whiskers indicate the minimum and maximum scores, black dots indicate outliers.

The results of these models are presented in Table 2.6, which shows that the mean daily air temperature is significantly lower in the GB than in CBs, with a mean difference of 2.26 °C. Mean daily relative humidity was also significantly lower in the GB, with a mean difference of 11.9%. On the other hand, mean daily CO_2 concentration was not significantly different across the two classes of building.

Table 2.6's overview of the model's random effects shows that month explained most of the variance in mean daily air temperatures (56%) once any differences attributable to green building status were accounted for. The month was a poorer predictor of RH, however, explaining only 12% of the variance in measurements, after green building status was accounted for. The majority of the variance in RH measures that could not be explained by green building status was still unexplained even after the month and building identity were included in the model and so must arise from variables we have not considered here.

The majority of residual variance in the mean CO_2 level was also left unexplained here, although it is notable that, for this outcome, individual building identity is a more important predictor for T_a and RH. Specifically, individual differences from one building to another accounted for 26% of the variance in CO_2 readings once any effects of green building status had been considered. This suggests that some buildings intrinsically and consistently have higher levels of CO_2 than others. Based on Figure 2.7, it appears that CB3 and GB generally have higher mean scores of CO_2 concentrations than the other three buildings.

Table 2.7 presents the mean, p-value and effect size (Cohen's d) for the spot measures of four thermal comfort metrics namely T_a, T_r, RH, and V_a conducted in Aug 2017 in CBs and Aug 2018 in the GB. These variables were used to calculate the PMV along with clo and met values. Also, Table 2.7 shows the results of the t-tests suggest rejecting the null hypothesis of no differences between the mean scores for all measured variables (p-value < 0.05), with medium to large effect size. The GB had a slightly lower mean of T_a and T_r compared to the CBs with a difference of 0.6 °C and 1.4 °C respectively. Similarly, the GB had lower mean of RH (mean = 36.6%, s = 3) compared to CBs (mean = 40.5%, s = 6.4). Observed indoor air speed in both building types was always less than 0.2 ms^{-1} (mean = 0.13 ms^{-1}, s = 0.11).

Table 2.6 The results of linear mixed effects models.

Outcome	Obs.	Intercept (95% CI)	Effect of green building status (95% CI)	Random effects			
				Total residual variance	Building ID	Month	Unexplained variance
Mean T_a (°C)	622	25.71 (23.86 – 27.55)	-2.26 (-4.07 – -0.45)	6.38	0.66 (10%)	3.56 (56%)	2.16 (34%)
Mean RH (%)	623	42.17 (41.40 – 42.94)	-11.89 (-13.11 – -10.67)	3.06	0.29 (9%)	0.38 (12%)	2.39 (78%)
Mean CO_2 (ppm)	473	559.40 (471.76 –647.04)	125.67 (-59.93 – 311.28)	27147.73	6979.16 (26%)	834.23 (3%)	19334.34 (71%)

Table 2.7 Results of t-test and descriptive statistics of data from spot measures of thermal conditions pre- and post-moving to the GB during Aug 2017 in CBs and Aug 2018 in the GB, ** p < 0.01, *** p < 0.001.

Parameter	CBs (Pre-moving) (M ± SD)	GB (Post-moving) (M ± SD)	CI 99%		t	df	p -value	Effect size (d)	
T_a (°C)	24.11 ± 1.65	23.52 ± 0.62	0.11	1.10	2.44	62.59	0.01**	0.48	Medium
T_r (°C)	25.32 ± 1.95	23.91 ± 0.80	0.95	2.11	4.76	65.20	0.00***	0.93	Large
RH (%)	40.51 ± 6.46	36.51 ± 3.00	2.02	6.04	3.99	69.10	0.00***	0.79	Large
V_a (ms^{-1})	0.09 ± 0.07	0.01 ± 0.00	0.06	0.10	8.28	49.00	0.00***	0.79	Large

2.7.2 Perceived comfort of IEQ

While the GB outperforms the CBs in terms of the measured thermal conditions (as seen in 2.7.1), it is necessary to obtain a picture of occupant perception of the obtained IEQ. Therefore, the occupants perceived comfort over thirteen perceptual IEQ metrics were compared between Phase I and Phase II. These metrics are grouped into five aspects: IAQ, temperature, visual comfort, acoustic comfort, and secondary metrics. Figure 2.8 compares between the two building types and shows the distribution of occupants' satisfaction towards the individual IEQ metrics, that were almost comparable among both study phases.

In the CBs, control lighting and odour had higher mean scores of satisfactions, whereas moving to the GB has increased the mean score of occupant satisfaction of view, fresh air, and temperature (winter). However, these differences were not statistically significant (p-value > 0.05), as illustrated in Table 2.8.

The results of the paired samples t-tests fail to reject the null hypothesis of no significant differences in the mean scores of occupant satisfaction between both building types for ten metrics, namely, noise, temperature (winter and summer), lighting, biophilia, privacy, view, air quality, and control over temperature and lighting (p-value > 0.05). The only significant differences in mean scores were observed in odour ($t(101) = -4.22, p = 0.001, d = 0.36$), mental concentration ($t(101) = -1.95, p = 0.02, d = 0.21$), and glare ($t(101) = 2.03$, $p = 0.04, d = 0.20$), which are seen to be statistically significant but with a small effect size. These three metrics had lower mean scores after moving, hence they were perceived worse in the GB. Therefore, it can be stated that occupants who moved to the GB did not show any notable improvement in the overall perceived comfort.

Figure 2.9 compares the overall mean scores of occupant satisfaction with all IEQ metrics in the CBs and GB, that were almost equal pre-moving (mean = 2.61) and post-moving (mean = 2.69). However, mean scores in both building types were lower than the neutral midpoint (i.e., three) on a scale ranged between strongly dissatisfied (1) and strongly satisfied (5) suggesting that at no point were occupants overall satisfied with their workplace, whether in the GB or not.

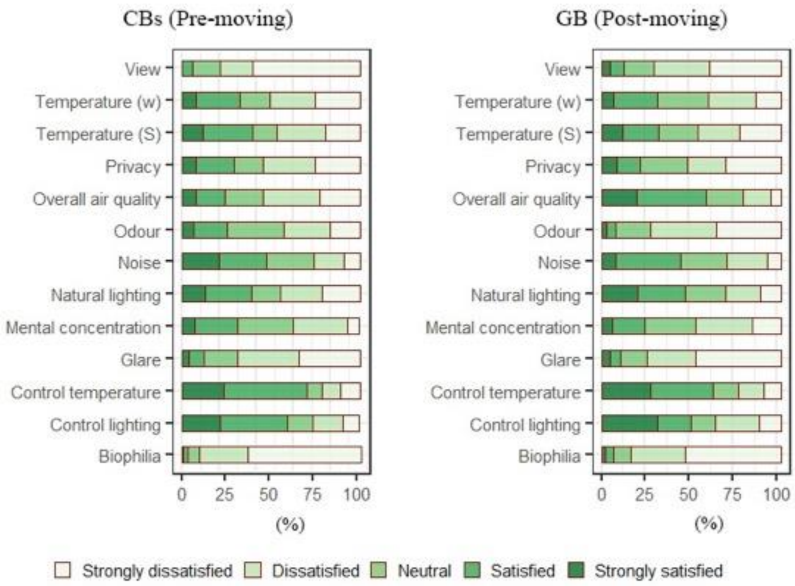

Figure 2.8 The distribution of occupant satisfaction of thirteen IEQ metrics pre- and post-moving to the GB, satisfaction score from (1) strongly dissatisfied to (5) strongly satisfied, and (3) represents the neutrality, $n\_CBs = 120, n\_GB = 102$, (statistical analysis in Table 2.8).

Table 2.8 Statistical analysis of differences in mean scores of occupant perceived comfort pre- and post-moving to the GB, * significant at p < 0.05; *** significant at p < 0.001; n.s. indicates not significant.

IEQ parameter	Mean score ∈ [1,5]		CI 99%		t	p-value	Effect size (d)	
	CBs (Pre-moving)	GB (Post-moving)						
IAQ								
Overall air quality	2.55	3.49	0.94	1.23	5.24	0.17 n.s.	0.13	Negligible
Temperature								
Temperature (winter)	2.65	2.8	0.15	0.45	0.97	0.33 n.s.	0.09	Negligible

Temperature (summer)	2.92	2.75	-0.16	0.14	-0.89	0.18 n.s.	0.04	Negligible
Control temperature	3.61	3.56	-0.04	0.25	-0.26	0.39 n.s.	0.06	Negligible
Visual comfort								
Natural lighting	2.85	3.23	0.37	0.67	2.02	0.97 n.s.	0.11	Small
Glare	2.17	1.94	-0.22	0.03	2.03	0.04*	0.20	Small
Control lighting	3.61	3.56	-0.04	0.25	-0.26	0.39 n.s.	0.06	Negligible
Acoustic comfort								
Noise	3.29	3.13	-0.16	0.09	-1.04	0.14 n.s.	0.17	Negligible
Mental concentration	2.95	2.65	-0.30	-0.04	-1.95	0.02*	0.21	Small
Secondary metrics								
Odour	2.72	2.03	-0.68	-0.41	-4.22	0.00***	0 .36	Small
Privacy	2.58	2.46	-0.11	0.21	-0.59	0.27 n.s.	0.12	Negligible
View	2.75	3.33	0.58	0.92	2.91	0.99 n.s.	0.04	Negligible
Biophilia	1.73	1.45	0.27	0.49	2.09	0.98 n.s.	0.15	Negligible

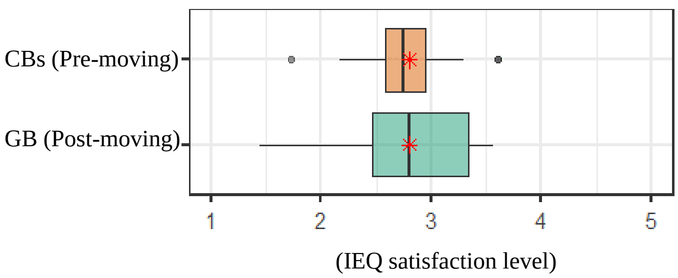

Figure 2.9 Overall mean score of occupant satisfaction in both study phases, satisfaction score from (1) strongly dissatisfied to (5) strongly satisfied, and (3) represents the neutrality, whiskers indicate the minimum and maximum scores, black dots indicate outliers, red star indicates mean score.

2.7.3 Thermal comfort

Figure 2.10 and Table 2.9 show the distribution of the observed Thermal Sensation Vote (TSV), Thermal Preference Vote (TPV), and calculated Predicted Mean Vote (PMV) pre- and post-moving to the GB. In CBs, only 72% of the TSV votes were within the ASHRAE 55 acceptable comfort zone of TSV between [-1 and +1], hence failing the 80% ASHRAE

acceptability threshold that is adopted by the JGBG. Although PMV predicts neutral to slightly warm, with 85% predicted to fall within the ISO 7730 recommended range of [-0.5, +0.5], 40% of the TSV votes fall within slightly cool (-1) to cool (-2) in the summer (
Figure 2.10 (Left)). This is supported by the TPV, as 48% of the occupants in CBs preferred a warmer indoor air temperature in their workplaces (
Figure 2.10 (Right)).

In contrast, in the GB, 87% of TSV votes fell within slightly warm (+1) or slightly cool (-1), which is broadly commensurate with the PMV prediction of 92% and are hence in the acceptable range. The TPV in the GB show compliance with the ASHRAE standard, as less than 20% of occupants preferred either a bit cooler or a bit warmer thermal environment.

Figure 2.11, compares the reported TSV by occupants and the predicted PMV in both building types. In the CBs, there was a statistically significant difference between mean score of TSV (-0.17) and PMV (0.05), while the PMV predicted neutrality, the majority of occupants' votes were on the cold side. Contrary to the GB, there was no statistical difference between the mans of observed TSV (0.09) and PMV (0.19), which both were close to the neutral (i.e., zero), thus a higher thermal comfort was observed in the GB.

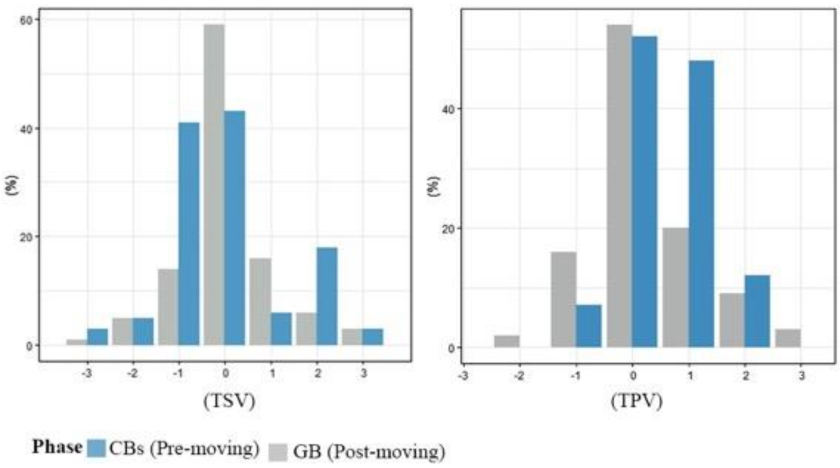

Figure 2.10 The distribution of the observed Thermal Sensation Votes (TSV) (Left), and Thermal Preference Votes (TPV) (Right), in both building types pre- and post-moving.

Table 2.9 Thermal acceptability percentages for objective and subjective measurements pre- and post-moving to the GB.

Building type	TSV (M ± SD)	PMV (M ± SD)	Acceptable range		
			-1 ≤ TSV ≤ +1	-0.5 ≤ PMV ≤ +0.5	- 1 ≤ TPV ≤ +1
CBs (Pre-moving)	-0.17 ± 1.31	0.05 ± 0.31	72%	85%	90%
GB (Post-moving)	0.09 ± 1.03	0.19 ± 0.27	87%	92%	88%

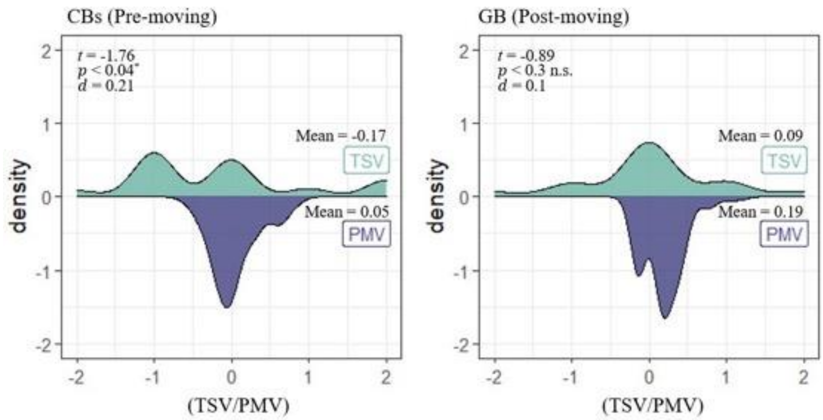

Figure 2.11 Comparison between the observed TSV and the predicted PMV by Fanger model in both building types, $n\_CBs = 120, n\_GB = 102$, * indicates significant difference, n.s. indicates no significant difference, (statistical analysis in Table 2.9).

2.7.4 Perceived health

Figure 2.12 shows the frequency of ten reported SBS symptoms pre- and post-moving to the GB. In both building types, the incidence of four symptoms namely ‘arms, legs and joints pain’, ‘muscle soreness’, ‘tiredness’, and ‘trouble sleeping’ was almost similar. Interestingly, in the GB, a higher prevalence of dizziness and fever symptoms was observed.

Table 2.10 presents the results of the paired samples *t*-test, which suggests rejecting the null hypothesis of no difference between mean scores of reported SBS for only two symptoms, namely tiredness ($t(101) = -2.95, p = 0.02, d = 0.31$) and watery eyes, runny nose, and stuffy head ($t(101) = -1.70, p = 0.04, d = 0.13$).

However, these findings should not be taken at face value. Our analysis of

Figure 2.12

involves ten *t*-tests, so we apply the Holm Bonferroni method to deal with family-wise error rate (FWER) for multiple hypothesis tests (Holm, 1979). When corrected, none of the SBS symptom *t*-tests were significant, and so we conclude that there appears to be no change in SBS symptoms after moving to the GB. Additionally, Table 2.11 illustrates the proportions of five frequency categories for all reported SBS symptoms in both building types. According to the ASHRAE standard 62.1 threshold, CBs and GB could be labelled as 'sick buildings', since 20% and 23% of their occupants respectively had experienced some of the SBS symptoms for 'some of the time' during working hours.

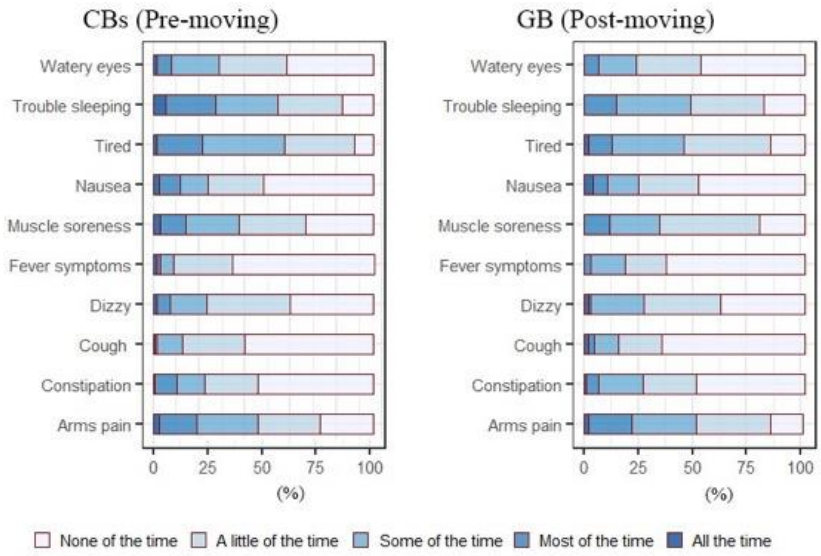

Figure 2.12 The distribution of occupant responses of each SBS symptom pre- and post-moving to the GB, $n\_CBs = 120, n\_GB = 102$, (statistical analysis in Table 2.10).

Table 2.10 Statistical analysis of differences in mean scores of occupants self-reported SBS symptoms pre- and post- moving to the GB, frequency score from (1) none of the time to (5) all the time, and (3) represents some of the time, corrected p-value indicates the p-value of Holm-Bonferroni-corrected test at an alpha level of 0.05.

Symptom	Mean ∈ [1,5]		CI 99%		t	Corrected p-value	Effect size (d)	
	CBs (Pre-moving)	GB (Post-moving)						
Tired	2.81	2.44	-0.37	-0.16	-2.95	0.20	0.31	Small
Watery eyes, runny nose, stuffy head	2.04	1.83	-0.21	0.00	-1.70	0.36	0.13	Small
Dizzy	2.36	1.94	-0.42	0.27	-0.97	1.00	0.10	Small
Trouble sleeping	2.56	2.44	-0.11	0.12	-0.81	1.00	0.08	Negligible
Back/neck pain	2.76	2.6	-0.16	0.09	-1.05	1.00	0.10	Small
Arms, legs and joints pain	2.46	2.42	-0.03	0.19	-0.27	1.00	0.02	Negligible
Muscle soreness	2.3	2.25	0.04	0.17	-0.36	1.00	0.02	Negligible
Cough/ sore throat	1.56	1.58	0.01	0.21	0.17	1.00	0.01	Negligible
Fever symptoms	1.46	1.59	0.12	0.31	1.12	1.00	0.11	Small
Constipation and loose bowels	1.84	1.85	0.00	0.25	0.06	1.00	0.00	Negligible

Table 2.11 Proportion of occupants who reported any of SBS symptoms in both building types, classified into five frequency categories.

Frequency of symptoms	CBs (Pre-moving)	GB (Post-moving)
None of the time	38%	38%
A little of the time	29%	30%
Some of the time	20%	23%
Most of the time	11%	8%
All the time	2%	1%

2.8 Discussion

Our results can be split into two parts: observed IEQ performance (i.e., thermal conditions + IAQ) and perceived performance, we discuss these below.

2.8.1 Thermal conditions and IAQ

Localised recommended ranges of indoor air temperature and CO_2 concentration levels are absent in the JGBG, which instead refers to ASHRAE 55 for determining the acceptable thermal comfort range and ASHRAE 62.1 for acceptable indoor CO_2 level. ASHRAE 55 suggests a temperature range between 21.5 °C – 27 °C (under the conditions of a thermal clothing insulation value between 0.5 and 1, metabolic rate between 1 and 1.3, and $V_a \leq 0.2$ ms^{-1}). Comparing our results of continuous monitoring of T_a in the surveyed buildings showed that in CBs, only 48% of recorded T_a fell in the acceptable indoor temperature range, while in the GB, this percentage was higher, as 62% of monitored T_a were within the recommended range.

Further, comparing the results of thermal conditions from spot measures (i.e., T_a, T_r, RH, and V_a) across building types showed a significant difference in the mean scores between the CBs and GB in all monitored variables with lower mean in the GB. The RH in the GB (mean = 36.5%, s = 3%) was significantly lower than the threshold of acceptability of 50% defined by JGBG. The monitored indoor air speed in both building types was within the JGBG recommended acceptable value (≤ 0.2 ms^{-1}).

The disparities in monitored thermal conditions between the CBs and GB were expected due to the variances of the building design approaches and the differences in heating, cooling, and ventilation systems. Further, behavioural adaptations (e.g., open/close windows, turn on/off the air-conditioning, and changing temperature set points) could play a role in the thermal conditions' variations between the two building types.

Surprisingly, a variation in the air temperature behaviour within the floors of GB was observed. Figure 2.13 shows that the top floor (F4) of the GB performed differently with a higher mean air temperature of (mean = 29 °C, s = 2.2 °C) across all monitored months compared to the mean air temperature of the other floors in the GB. This disparity is attributable to several reasons: (i) unlike the other floors, the top floor was 30% occupied during the monitored period, and as each floor is controlled individually by the operating manager, the AC system on this floor was turned off to account for this. (ii) Solar gains are likely to have been higher in the top floor compared to the bottom floors, and (iii) a covered glazed void on the south side for daylighting links all floors vertically, possibly trapping air moving upwards due to the stack effect.

Turning to the result of monitored indoor CO_2 concentration levels, it shows that though GB and CB3 had higher mean scores of indoor CO_2 levels compared to other monitored buildings as shown in Figure 2.7, all buildings had achieved the ASHRAE 62.1 recommended standard for CO2 of 1,100 ppm inside workplaces for an 8-hr workday (ANSI/ASHRAE 62.1, 2010).

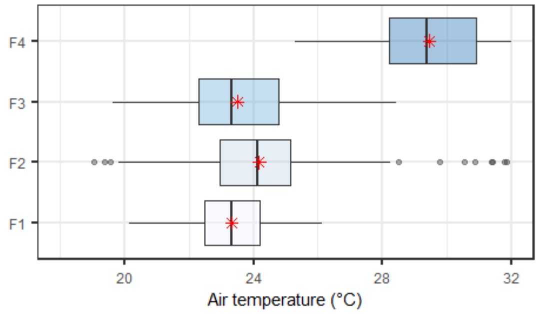

Figure 2.13 The difference in mean scores of monitored indoor air temperature between the monitored four floors in the GB, data recorded between Jul 2018 and Feb 2019, whiskers indicate the minimum and maximum scores, black dots indicate outliers, the red star indicates mean score for each floor.

2.8.2 Occupant perception, thermal comfort and SBS

Contrary to expectations, occupant satisfaction of IEQ does not show a significant difference between CBs and GB, excepting in three metrics namely odour, glare and mental concentration. While these were perceived to be significantly worse after moving to the GB, the effect sizes were small. Speculative reasons for the worsened odour perception in the GB could be: (i) indoor emissions derived from the building itself (e.g., furnishing, personal products of employees, cleaning products, and office machines), as the GB has sealed envelope, this makes the odour more noticeable by occupants; and (ii) outdoor emissions included vehicle exhausts nearby entering the building air intake are distributed by the mechanical ventilation system in the entire floor.

Moreover, a possible explanation for the decline in occupant satisfaction of glare and mental concentration after moving to the GB might be that bullpen workplace with insufficient lighting distribution and poor control in the GB may be considered “chaotic” (Danielsson, Wulff and Theorell, 2015). Only 30% of occupants in the GB can adjust the light intensity in their workplaces, and this could increase stress level and negatively affecting employee mental concentration.

However, the overall mean scores of all IEQ satisfaction voted by occupants in both building types were comparable and below the neutral midpoint as shown in Figure 2.9, hence, we can consider that occupants perceived the GB and CBs to be broadly similar, in that neither was particularly nice. Unlike the majority of studies in localised GBCs from different countries (Table 2.1), the JGBG building in this study is not seen to improve occupant perception of IEQ. This finding is consistent with an earlier study, which had a similar research design, following a group of workers after the transition from conventional building to the first Green Star-building in South Africa (Thatcher and Milner, 2012).

Furthermore, we could speculate the lack of any improvement in occupant perception after moving to the GB to that participants' values and attitudes were not pro-environmental. As in both study phases, the mean score of the Environmental Attitude Inventory (EAI) for the whole dataset was (3.61, s = 1.07). This is very close to the midpoint of the scale mean score, i.e., three.

The mean of EAI was almost equal in the CBs (3.68) and GB (3.55) (Figure 2.14). This indicates that participants had a similar environmental concern level pre- and post-moving to the GB and, as this was not particularly high, we might speculate that moving to the GB is unlikely to have activated green attitudes or self-identities in most people, which in turn might be expected to lead people to evaluate the GB favourably.

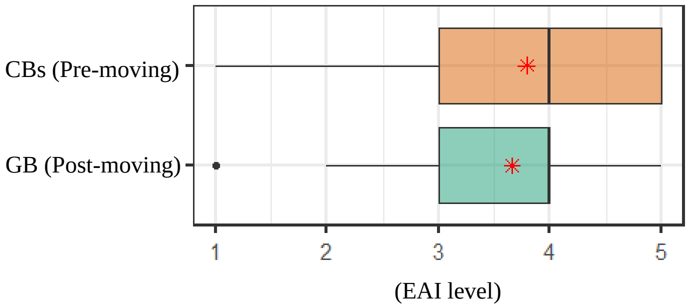

Figure 2.14 The difference in mean scores of occupants' Environmental Attitude pre- and post- moving to the GB, scale ranged between (1) strongly disagree (5) strongly agree, and (3) represents no opinion or the neutrality, whiskers indicate the minimum and maximum scores, black dots indicate outliers, red star represents mean score.

Turning now to the evidence of thermal comfort that suggests the presence of "overcooling" in the CBs, well known to exist in air-conditioned buildings in many parts of the world (Sekhar, 2016). This overcooling could be referred to the improper distribution of cool air from the split air conditioner units in the workplaces in CBs.

However, the presence of this overcooling disappears after the move to the GB despite the fact that average indoor temperatures fell after moving. Our results are consistent with several studies that observed green buildings exhibits superior performance in terms of thermal comfort compared to other IEQ aspects, such as visual and acoustic comfort or other secondary metrics, i.e. privacy (Abbaszadeh *et al.*, 2006; Thomas, 2010; Lin *et al.*, 2016).

Another important finding was that no significant differences were observed in the mean scores of all SBS symptoms between both building types. We found that 20% and 23% of occupants in CBs and the GB respectively experienced SBS symptoms for 'some of the time', therefore, both building types fail the ASHRAE 62.1 threshold. This is a remarkable, and concerning, outcome for any modern building, and raises questions about whether building codes and practices are adequate.

In CBs, five symptoms were experienced frequently by more than 20% of the occupants, these symptoms were back or neck pain (28%), tiredness (38%), watery eyes, runny nose and stuffy head (22%), muscle soreness (24%) and trouble sleeping (28%). After moving to the GB, the same proportion of occupants experienced the same five symptoms, with higher prevalence in trouble sleeping (33%). The dizziness was perceived as a problem by 25% of the occupants in the GB. What is surprising is that the percentage of occupants who had fever and flu symptoms has increased from 6% in CBs to 16% after moving to the GB. The high prevalence of these observed symptoms in the GB could be explained according to the following three factors:

- Plan-layout: The GB has a bullpen layout which is known to spread pathogens easily. For example, it has been shown that in congested open-plan workplaces, respiratory and fever symptoms can be spread faster due to the short distances between workstations (Habchi *et al.*, 2016).
- Natural light: As the GB is a deep-plan, the daylight and the visual connection to the outdoor were poor and this may lead to fatigue and trouble sleeping (WGBC, 2016).
- Building envelope: The GB in this study is sealed with no operable windows to prevent any thermal loss, so increase the energy efficiency, this may lead to 'Tight Building Syndrome', which causes particular health symptoms including dizziness, fatigue and sneezing (Rogers, 1987). However, the success of many Passivhaus buildings, which are built to the strictest airtightness standards

globally, and the general trend towards tighter construction would suggest that other vectors may also be in play, meriting further investigation.

Overall, in spite of the vital role of GBCs in the current green building development that resulted in vast reduction of energy use and operational costs, a building's green credentials should be viewed as completely orthogonal to its comfort and health credits. GBCs need to be amended and expanded based on building users' perception to include their health, physical and psychological aspects.

2.9 Conclusions

This study set out to examine whether the localised GBCs improve the performance of IEQ and occupant feedback in green buildings. We focus on the JGBG in Jordan, the results have shown that moving from conventional office buildings to the JGBG-certified building did not automatically guarantee a significant improvement in the employee perceived comfort and perceived health.

We find that despite the green building complied with the requirements of JGBG for thermal conditions and indoor CO_2 concentration level, no significant improvement in the occupant satisfaction of IEQ metrics was detected. In both building types, the mean of occupant satisfaction was small compared to the neutral midpoint. However, a modest improvement in the occupant thermal comfort was observed after moving to the GB.

Another major finding was that no significant improvement in the prevalence of SBS symptoms was reported after moving to the GB. In CBs, around 20% of occupants had experienced five SBS symptoms for 'some of the time', and this percentage has increased to 23% of occupants after moving to the GB. Hence, both building types could be labelled as "sick", according to the ASHRAE 62.1 standard – a remarkable, and disturbing, finding for any modern building.

Based on the evidence of this study, we suggest that green building designers, developers and policymakers pay greater attention to the occupants' related aspects. While reducing energy consumption and consequent emissions are undoubtedly important, designers of green buildings should think beyond these features, towards improving employee health, visual and acoustic comfort.

This would suggest the need for developing a follow-up management plan, that can be a part of the green building certification scheme. This plan might include regular assessments with two themes, i.e., objective and subjective that cover the building itself and its occupants. The assessment could be repeated every 12-month, as our results show no significant differences in occupant feedback between the first wave (6-month post-moving) and the second wave (12-month post-moving). This enables developers to benefit from occupant feedback in further IEQ developments in green buildings.

2.10 Acknowledgment and Data Statement

The authors would like to thank the Jordanian Green Building Council for their support and to thank Mr Mualla for helping with the data collection, Dr McCullen for assistance with Raspberry-Pi devices, the management of the surveyed buildings and their employees for their participation.
All data can be found at https://doi.org/10.15125/BATH-00925.

2.11 Funding

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2.12 Disclosure statement

The authors reported no potential conflict of interest.

2.13 Appendices

(a) Specifications of instruments used in monitoring indoor environment parameters.

Measurement type	Sensor	Variable	Unit	Valid Range	Accuracy
Spot measurements	SWEMA (ISO 7730)	T_a	°C	[0, 50]	±0.1
		RH	%	[0, 100]	±0.8
		V_a	ms-1	[0.1, 5]	±0.2
Continuous measurements (Raspberry Pi-based sensors)	Maxim IC DS18B20	T_a	°C	[-10, 85]	±0.5
	AdaFruit DHT22	RH	%	[0, 100]	±2
	Sensair K30	CO_2	ppm	[0, 5000]	±30

(b) Survey used in this study.

Organization:	Date:	Time:	Subject ID:
Demographic			

Age	Gender	Your Role	How long have you been working at this company?	Nationality	Education level
20-30 31-40 41-50 51 or more	Female Male	Administrative Design Marketing Executive Other	≤ 6 months 6-month - 1 year 1 year - 2.5 years 2.5 - 5 years ≥ 5 years	Jordanian Non-Jordanian	Not graduate High school graduate College 2-year Holding B.Sc. Holding M.Sc.

Indoor Environment Quality						
From scale 1 -5 how much do you satisfy with the following		Strongly Dissatisfied	Dissatisfied	Neutral	Satisfied	Strongly satisfied
		1	2	3	4	5
1	Overall air quality					
2	Temperature (winter)					
3	Temperature (summer)					
4	Control temperature					
5	Natural lighting					
6	Glare					
7	Control lighting					
8	Noise					
9	Mental concentration					
10	Odour					
11	Privacy					
12	View					
13	Biophilia					
Thoughts on the Natural Environment						
From scale 1 -5 how much do you agree with the following:		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1	I am the type of person who cares about the environment					
2	We are approaching the limit of the number of people the Earth can support					
3	Humans have the right to modify the natural environment to suit their needs					
4	When humans interfere with nature it often produces disastrous consequences					

5	Human ingenuity will ensure that we do NOT make the Earth unlivable					
6	Humans are severely abusing the environment					
7	The Earth has plenty of natural resources if we just learn how to develop them					
8	Plants and animals have just as much rights as humans to exist					
Sick Building Syndrome						
During the past 4 weeks (28 days), how much were you bothered by each of the following conditions:		Not at all	A little	Some of	Most of	All of the time
		1	2	3	4	5
1	Tired					
2	Watery eyes, runny nose, stuffy head					
3	Dizzy					
4	Trouble sleeping					
5	Back/neck pain					
6	Arms, legs and joints pain					
7	Muscle soreness					
8	Cough/ sore throat					
9	Fever symptoms					
10	Constipation and loose bowels					

At present, you feel:							
	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
	-3	-2	-1	0	+1	+2	+3
At present, you would prefer to be:							
	Much cooler	cooler	A bit cooler	No Change	A bit warmer	Warmer	Much warmer
	-3	-2	-1	0	+1	+2	+3

Your clothes at present (Please tick)		What is your activity during the past 15 minutes (Please tick)	
Short Sleeve shirt/blouse		Sitting (passive work	
Long sleeve shirt/blouse		Sitting (active work)	
Vest		Standing relaxed	
Trousers/long skirt		Standing working	
Shorts		Walking indoors	
Dress		Walking outdoors	

Pullover		Other………………	
Jacket		Instantaneous Measurements (for researcher only)	
Long socks			
Short socks		Air Velocity (ms^{-1})	
Tights		Air Temperature (°C)	
Tie		Relative Humidity (%)	
Boots		Mean radiant temperature (°C)	
Shoes		CO_2 level (ppm)	
Sandals			
Headwear			
Barefoot			

(c) Sociodemographic information of the respondents.

Category	n_occupants = 120	
Gender		
Female	42	(35%)
Male	78	(65%)
Age		
20 - 30	61	(51%)
31 - 40	44	(37%)
41 - 50	11	(9%)
≥ 50	4	(3%)
Working position		
Administrative	20	(17%)
Design	16	(13%)
Marketing	24	(20%)
Executive	21	(18%)
Other	39	(33%)
Working experience		
≤ 6 months	17	(14%)
6-month - 1 year	19	(16%)
1 year - 2.5 years	31	(26%)
2.5 - 5 Years	22	(18%)
≥ 5 Years	31	(26%)
Education level		
Not graduated	6	(5%)
High school	7	(6%)
College 2 years	10	(8%)
Bachelor	85	(71%)
Master	12	(10%)
Nationality		
Jordanian	116	(97%)
Non-Jordanian	4	(3%)

(d.1) Statistical analysis of differences in mean scores of occupant satisfaction of IEQ between the first wave (6-month post-moving to GB) and second wave (12-month post-moving to GB), n.s. indicates not significant.

	Mean						
IEQ parameter	6-month	12-month	CI 99%		t	p-value	Effect size (d)
IAQ							
Overall air quality	3.05	3.49	0.87	0.91	6.24	0.61 n.s.	0.11 (Small)
Temperature							
Feeling cold	2.45	2.8	0.11	0.55	0.87	0.42 n.s.	0.12 (Small)
Feeling hot	2.77	2.75	0.18	0.21	0.77	0.08 n.s.	0.13 (Small)
Control temperature	3.55	3.56	0.14	0.15	0.31	0.45 n.s.	0.08 (Negligible)
Visual comfort							
Natural lighting	3.22	3.23	0.35	0.59	2.55	0.19 n.s.	0.01 (Negligible)
Glare	1.82	1.94	-0.31	0.09	3.11	0.07 n.s.	0.08 (Negligible)
Control lighting	3.45	3.56	0.14	0.35	0.28	0.45 n.s.	0.14 (Small)
Acoustic comfort							
Noise	3.61	3.13	0.21	0.15	2.11	0.12 n.s.	0.15 (Small)
Mental concentration	2.45	2.65	0.22	0.07	1.65	0.06 n.s.	0.08 (Negligible)
Secondary metrics							
Odour	2.01	2.03	0.53	0.38	1.12	0.21 n.s.	0.14 (Small)
Privacy	2.39	2.46	-0.23	0.23	-0.63	0.39 n.s.	0.11 (Small)
View	2.85	3.33	0.61	0.13	3.11	1.11 n.s.	0.09 (Negligible)
Biophilia	1.60	1.45	0.31	0.55	2.5	0.79 n.s.	0.13 (Small)

(d.2) Statistical analysis of differences in mean scores of self-reported SBS symptoms between the first wave (6-month post-moving to GB) and second wave (12-month post-moving to GB); n.s. indicates not significant.

	Mean						
Symptom	6-month	12-month	CI 99%		t	p-value	Effect size (d)
Tired	2.55	2.44	0.29	0.21	3.21	0.09 n.s.	0.11 (Small)
Watery eyes, runny nose, stuffy head	2.11	1.83	-0.12	0.01	-1.55	0.14 n.s.	0.19 (Small)
Dizzy	2.21	1.94	0.56	0.31	0.89	0.41 n.s.	0.15 (Small)
Trouble sleeping	2.61	2.44	-0.13	0.09	-0.95	0.53 n.s.	0.12 (Small)
Back/neck pain	2.81	2.6	0.19	0.12	0.09	0.33 n.s.	0.08 (Negligible)
Arms, legs and joints pain	2.56	2.42	0.13	0.19	-0.27	0.81 n.s.	0.02 (Negligible)

Muscle soreness	2.28	2.25	0.13	0.21	-0.41	0.52 n.s.	0.06 (Negligible)
Cough/ sore throat	1.45	1.58	0.21	0.31	0.21	0.71 n.s.	0.09 (Negligible)
Fever symptoms	1.58	1.59	0.14	0.27	2.22	0.15 n.s.	0.08 (Negligible)
Constipation and loose bowels	1.88	1.85	0.01	0.09	0.08	0.70 n.s.	0.00 (Negligible)

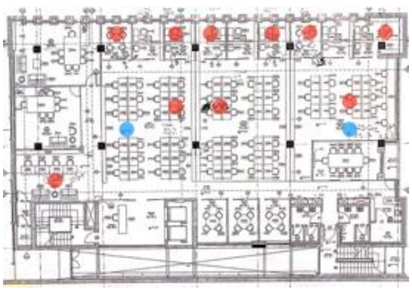
2.14 Addendum

This section has been added and is not a part of the published manuscript. It contains detailed information about the location of sensors in all surveyed buildings in this study: green-certified and conventional buildings.

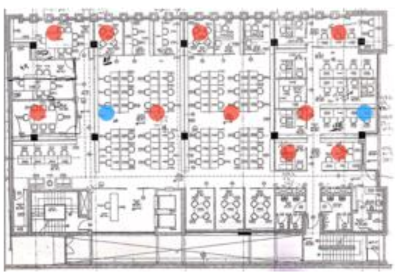
Note: red circle represents T_a + RH sensors and blue circle represents CO_2 sensor.

a) Location of sensors in green-certified building

GB-1st Floor

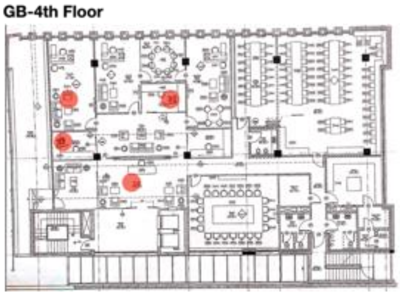


GB-2nd Floor



GB-3rd Floor

GB-4th Floor



b) Location of sensors in four conventional buildings

CB4

2.15 Postscript

This chapter aims to assess the role of localised GBCs in improving the performance of IEQ, occupant satisfaction and perceived health in green-certified office buildings. The main findings of this chapter are the following:

- Moving from conventional buildings to the JGBG-certified building did not improve the occupants’ satisfaction with IEQ or perceived health.
- Despite the JGBG-certified building meets the standard specification of thermal conditions and indoor CO_2 concentration levels, no significant improvement in the occupants' satisfaction with IEQ was detected.
- A slight improvement in occupant thermal comfort was observed across the move to the GB .
- The percentage of occupants who reported SBS symptoms has increased three percentage points after moving to the GB. Similarly, the percentage of occupants who experienced fever and flu symptoms has increased by 10 percentage points after transition.

Overall, this case study showed that although green-certified building meets the specifications of JGBG for thermal comfort and indoor CO_2 level, it failed to improve the occupant satisfaction with IEQ and perceived health. Further, this chapter highlighted the IEQ factors that may affect the prevalence of SBS symptoms, and suggested measures that can be followed to prevent the increase of SBS in workplaces. Findings from this chapter pointed out the need for a wider investigation that cover other green buildings are designed and certified to other GBCs. This can help to understand in depth the performance gap between design estimations and effective performance of buildings in use, this is investigated in the following chapter.

3 Indoor environment quality and work performance in “green” office buildings in the Middle East

3.1 Preamble

This chapter expands the investigation that was presented in Chapter 2. In this chapter, I focus on LEED-certified office buildings. This is the first study of its kind in the ME, which is experiencing significant growth in the overall number of green buildings, while there remains a paucity of evidence of the actual performance of green buildings in this region. The LEED office buildings in Jordan were selected as relevant examples of LEED buildings in the ME to be investigated.

This chapter aims to investigate whether LEED office buildings achieve the required minimum IEQ standards in terms of thermal conditions and indoor air quality, during occupancy stage, and if so, whether occupants of these buildings are satisfied with their IEQ and demonstrated better work performance compared to their counterparts in conventional buildings. Further, this chapter identifies the main concerns of IEQ perceived by the occupants in LEED buildings, also, it investigates the most IEQ aspects that may negatively influence the employee work performance.

Our systematic evaluation has included two aspects of POE, which were done in LEED-certified-buildings and CBs:

1. Objective measures of IEQ aspects included monitoring of thermal conditions (e.g., air temperature, mean radiant temperature, air speed, relative humidity) and indoor CO_2 concentration levels as an indicator of IAQ.
2. Subjective measures covering 502 employees and assess their satisfaction of four IEQ aspects (i.e., IAQ, thermal, visual and acoustic comfort), also assess the work performance of employees by measuring two metrics (i.e., absenteeism and presenteeism rates).

3.2 Declaration of authorship

This declaration concerns the article entitled:
Indoor environment quality and work performance in "green" office buildings in the Middle East
Publication status (tick one)
Submitted ☐ In review ☐ Accepted ☐ Published ☑
Publication details:
R. Elnaklah, D. Fosas, S. Natarajan, Indoor environment quality and work performance in "green" office buildings in the Middle East, Building Simulation. 13 (2020) 1043–1062. https://doi.org/10.1007/s12273-020-0695-1.
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• Formulation of ideas: R. Elnaklah (80%) and S. Natarajan (20%). • Design of Methodology: R. Elnaklah (80%) and S. Natarajan (20%). • Data Collection: R. Elnaklah (100%). • Data Analysis: R. Elnaklah (80%), D. Fosas (10%) and S. Natarajan (10%). • Presentation of data in journal format: R. Elnaklah (80%) and S. Natarajan (20%).
Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.
Signed: Rana Elnaklah **Date:** 30th Nov 2020

3.3 Abstract

Globally, a primary concern is whether green office buildings perform as promised in terms of providing better Indoor Environment Quality (IEQ) for employees, which may affect their satisfaction and work performance. In the Middle East, although there has

been renewed interest in green building design, post occupancy evaluation of performance has never been conducted to-date, and evidence of actual occupant perception in green and non-green buildings is still ambiguous. Hence, we present the first study on IEQ performance in the Middle East. We show that Jordan can be taken as a representative example and systematically compare five “green” office buildings (representing 71% of all green-certified office buildings) against eight comparable conventional office buildings (CBs).

Detailed bi-lingual survey data on perceived IEQ (n=502) and work performance are accompanied by high-resolution continuous physical measurements of air temperature + relative humidity (n=83) and CO_2 concentrations (n=21) with periodic measurements of mean radiant temperature and air speed, covering two typical summers and one typical winter.

Results show both building types comply with design standards for indoor CO_2 levels, while thermal comfort in green buildings is better than in CBs. However, CBs have a higher overall occupant satisfaction of IEQ. Work performance measured as absolute and relative absenteeism was slightly higher in CBs, with no significant differences in relative and absolute presenteeism between the two buildings types. These findings challenge the notion that green buildings improve occupant satisfaction and work performance over CBs and suggest the need for a better understanding of the performance ↔ satisfaction gap.

3.4 Introduction

Buildings consume 48% of global energy, and they are responsible for a quarter of global carbon emissions (IEA, 2019a). The desire to reduce their energy use and greenhouse gas emissions has resulted in an increasing interest in ‘green buildings’ (IEA, 2013). Although there is no formal definition of this term, a ‘green building’ conventionally refers to a building that is designed to be efficient in the consumption of natural resources, while conserving energy, reducing harmful impact on the environment, and improving quality of life for users (EPA, 2019).

This resulted in the creation of several building design standards all over the world, but of which the earliest, i.e. BREEAM (Building Research Establishment Environmental Assessment Method) established in 1990 in the United Kingdom (BREEAM, 2019), and LEED (Leadership in Energy and Environmental Design) launched in 1998 in the United

States (USGBC, 2019), are the most widespread, being used in 70 and 162 countries respectively. These standards cover the design, construction, delivery and operation of buildings, and they are used to evaluate the potential of a building to be energy efficient, with reduced environmental impact, and the ability to provide an adequate indoor environment for users (Wei, Ramalho and Mandin, 2015).

Although most green building standards are applicable to a range of building types, e.g., schools, residential, healthcare and offices, it is the last of these that has seen the greatest adoption. For example, office buildings are the largest single category of LEED buildings globally, representing 41% of LEED stock (USGBC, 2019). According to the World Green Building Council (WGBC) three factors, apart from their reduced environmental impact, have driven demand for the construction of green offices: (i) investors and stakeholders recognising the potential for reduced operational costs through a reduction in building energy demand; (ii) reputational benefit through association with positive "green" branding and (iii) improved employee satisfaction and work performance[3] through improved Indoor Environment Quality (IEQ) (WGBC, 2016).

Since IEQ plays an important role for both companies and their occupants, it is worth investigating it in detail. IEQ is defined as "the quality of a building's environment in relation to the health and wellbeing of those who occupy space within it" (CDC, 2020). It refers mainly to four parameters, namely Indoor Air Quality (IAQ) and thermal, visual and acoustic comfort (ISO 17772-1, 2017). These aspects have a direct effect on the occupant comfort, health, and wellbeing. In addition, according to the WGBC, other secondary physical factors of indoor environment (e.g., layout, aesthetics, amenities, and biophilia) could also play a role in the occupant comfort and satisfaction (WGBC, 2016).

As a result of the climate change agenda, there have been international efforts like the Kyoto Protocol (UNFCCC, 1998) or the Energy Performance of Buildings Directive (EPBD) in the European Union (European Parliament, 2010; The European Parliament and the Council of the European Union, 2018), to link the high level of energy performance with the high level of IEQ in buildings. Further, there is growing recognition that the savings in operational costs from green buildings pale in comparison to the likely improvements in work performance emerging from factors such as reduced absenteeism and presenteeism. This is because 90% of the typical operational cost of a business goes towards employee salary and benefits as opposed to only 1% on the operational energy

[3] This term is formally defined in Section 3.5.2.

of the building (WGBC, 2014). Moreover, given that employees spend at least 24% of their time in a typical week at their workplaces and, in many instances, with poor control over the indoor environmental conditions (e.g., space conditioning, lighting, window control), it is clear that improved IEQ could provide a direct pathway for improved occupant satisfaction and work performance.

However, occupant satisfaction is perceptual rather than objective and hence data is needed over several buildings to reduce the effect of aleatory uncertainties. Similarly, work performance is a secondary measure of the effect of the indoor environment and is hence subject to the effect of other confounding factors.

Despite WGBC's reported benefits of improved in IEQ of green buildings, it is unclear whether green office buildings really perform better in terms of IEQ and increase employee satisfaction or work performance (Veitch *et al.*, 2007; Fostervold and Nersveen, 2008; Altomonte and Schiavon, 2013; Gou, Prasad and Lau, 2013; Ravindu *et al.*, 2015; Tham, Wargocki and Tan, 2015; Sediso and Lee, 2016). Some evidence suggests that though green buildings might achieve their energy efficiency targets (WGBC, 2016), they may also exhibit unintended consequences that reduce the quality of indoor environment and curtail occupant satisfaction. For example, green buildings with airtight envelope and poorly thought out ventilation can end up with poor air quality that might lead to increase the health problems and discomfort between occupants (Leaman and Bordass, 2007b; Brown and Cole, 2009; Armitage, Murugan and Kato, 2011; Davies and Oreszczyn, 2012; Collinge *et al.*, 2014).

Although standards such as ISO 52003 (EN ISO 52003-1, 2017) and EPBD (The European Parliament and the Council of the European Union, 2018) highlight the importance of creating a balance between the high energy performance of buildings and providing a proper IEQ, historically there has been a lower emphasis on IEQ compared to energy and carbon, due to the climate change imperative.

Most green building rating tools include minimum standards for IEQ and some even consider it as a design parameter through which the score of the building can be enhanced. However, when included, IEQ is typically weighted with lower credits compared to other green design aspects such as energy efficiency (Table 3.1). In a review of 31 global green rating systems, IAQ was found to contribute an average of only 7.5% of the total score (Wei, Ramalho and Mandin, 2015). For example, LEED rates buildings as either "Certified", "Silver", "Gold" or "Platinum", according to the scores they achieve, where 'Certified' represents the lowest possible achievement and 'Platinum' the highest.

A building achieves LEED "Platinum" if it achieves at least 80 out of the 110 possible points, something attainable without addressing any of the extra IAQ points, such as increasing the ventilation rate 30% more than the minimum required rate, using low Volatile Organic Compound (VOC) painting and furniture, and providing the building with localised sensors of Carbon Monoxide (CO) and Carbon Dioxide (CO_2). In practice, certified projects seem to address the compulsory IEQ aspects plus any other extra points or credits that are cost-effective and easy to apply (Srebric, 2010). In addition, Section 6 'IEQ' in the LEED standard requires conducting baseline IAQ testing as part of the IAQ management plan. This should be done twice, one after the construction stage and the other prior to occupation, usually within 30 to 60 days of issuing the certificate (USGBC, 2019). Therefore, this does not account for in-use conditions. The lower attention to IEQ compared to other aspects, especially energy efficiency, can be explained by the initial goal of developing the green building rating tools, which was primarily one of lowering building energy demand.

Taking the Middle East as an example, the population grew at an average rate of 1.7% per year between 1999 and 2019. This was associated with a growth in the energy demand for heating and cooling of 10% per year, compared to 0.4% per year in OECD (Organization for Economic Co-operation and Development) countries over the same period (IEA, 2019a). In response to this, governments in the Middle East produced new building standards geared towards the production of more energy efficient and sustainable buildings. In fact, all but Iraq, Syria, and Yemen in the Middle East now have their own green building standards.

However, the adoption of such standards in the Middle East faces three challenges: (i) lack of public awareness of the direct and in-direct benefits of green buildings (Al Horr *et al.*, 2016); (ii) lack of trained/educated green building professionals that may affect design, construction, or follow-up stages, and (iii) investors associate green design features with costly technologies that threatens the profitability of a project (DODGE, 2018). Indeed, these issues are shared across the developing world where the most aggressive growth in global building construction is projected to occur over the next 30 years (Gobbi, Puglisi and Ciaramella, 2016), raising questions around the viability of these standards in the long term. Unfortunately, little research exists on the as-built performance of green buildings in the Middle East, which would aid in improving awareness while either allaying or confirming concerns around their costs. Studies that do exist focus primarily on the residential sector and, unsurprisingly, attempt to assess the energy performance rather than IEQ of the buildings (Hassouneh, Al-Salaymeh and Qoussous, 2015). No study heretofore has considered the occupants' perception in green buildings in this region in the surveyed literature.

Table 3.1 Relative weighting of energy efficiency and IEQ aspects used in two of the most popular global standards (LEED and BREEAM) and in five standards local to the Middle East.

Country	Green Building Standard	Relative Weighting (%)	
		Energy Efficiency	IEQ
United States	LEED	32%	14%
United Kingdom	BREEAM	19%	15%
Jordan	JGBG	39%	9%
Qatar	GSAS	72%	42%
United Arab Emirates	PBRS	44%	37%
Israel	SI 5281	40%	18%
Egypt	GPRS	25%	10%

3.5 Literature review

Given the paucity of literature on green buildings and their impact on occupants in the Middle East, we provide an overview of studies from other parts of the world as a means to understand the key issues.

3.5.1 Research on IEQ in green office buildings

As we observed in Section 3.4, all green rating tools directly address IEQ and hence there is an expectation that green office buildings will provide better IEQ, resulting in increased employee satisfaction and work performance. However, this remains a debated question despite the numerous studies addressing IEQ in green offices (Newsham *et al.*, 2013; Gou, Prasad and Lau, 2014; Pei *et al.*, 2015; Ravindu *et al.*, 2015; Tham, Wargocki and Tan, 2015; MacNaughton *et al.*, 2016; Sediso and Lee, 2016). The two most debated IEQ aspects in green office buildings in the literature over the past two decades have been thermal comfort and IAQ. Table 3.2 groups these studies according to methods and outcomes. From a methodological standpoint, the overall approach used by all these studies can be classed under the umbrella term Post Occupancy Evaluation (POE). There are several methods of undertaking a POE assessment (e.g., TM22 (CIBSE, 2019), (BUS Methodology, 2019), BePAD (Oxford Brookes University, 2019)) but they will usually consider one or more of three complementary aspects:

Aspect I Subjective assessment of building performance via occupant feedback (questionnaire, focus group or interviews) (ISO 10551, 2019);

Aspect II Objective assessment of energy consumption (e.g., via utility bills or detailed measurement) (CEN ISO/TR 52000-2, 2017); and

Aspect III Measurements of physical IEQ parameters including: (i) thermal comfort indicators (e.g., air temperature (T_a), mean radiant temperature (T_r), air speed (V_a), and relative humidity (RH)), (ii) IAQ indicators (e.g., carbon dioxide (CO_2), carbon monoxide (CO), and other pollutant metrics), (iii) visual comfort, and (iv) acoustic comfort. The as-built performance of the building is then compared to design goals and against occupant feedback to appraise the relative merits of the final building (e.g., EN ISO 7726 (EN ISO 7726, 2001); ISO 16814 (ISO 16814, 2008); EN ISO 3382-3 (EN ISO 3382-3, 2012); ISO 16817 (ISO 16817, 2017)).

In terms of outcomes, we group findings with respect to the differential impact green buildings have on occupant satisfaction when compared to conventional buildings or to national benchmarks, when considering thermal comfort and IAQ. For both thermal comfort and IAQ, studies grouped under the label 'A' suggest greater occupant satisfaction in green buildings whereas those grouped as 'B' and 'C' show lower satisfaction or no difference, respectively.

We observe that although there are fewer studies falling into Group B (i.e., green buildings showing lower satisfaction), this group contains the study with the highest overall sample size (Altomonte and Schiavon, 2013) which covers a large number of global buildings. Unfortunately, these results are based primarily on occupant perception (Aspect I) rather than measured IEQ (Aspect III). Indeed, only one study in this group uses an Aspect III measurement and control group (i.e., non-green buildings) (Ravindu *et al.*, 2015).

Similarly, only three out of the nine studies in Group A (i.e., green buildings showing higher satisfaction) contain a control group as well as Aspect III measurements. In these studies, a strong alignment was observed between measured and perceived IEQ, suggesting that coincident Aspect III measurements are needed for a holistic assessment of performance.

A key deficiency of the published literature, in general, is the broad reliance on *p*-values for significance testing (14 out of 16) but the lack of accompanying analysis of effect size (7 out of 13). It is well-known that a lack of expression of effect sizes can lead to erroneous conclusions about true significance (for example, a *t*-test suggesting significant difference in mean indoor operative temperatures when the difference is 0.1 °C). Finally, although a small number of developing countries (Sri Lanka, South Africa, and China) are represented in these studies, responses are heavily weighted towards industrialised countries. Indeed, the Middle East is currently unrepresented, supporting the case for studies in this region.

Table 3.2 Summary of studies investigating the perception and satisfaction of thermal comfort (TC) and IAQ in green buildings compared to conventional buildings, benchmark or to the scale midpoint.

Study	Country	Buildings covered		Occupants surveyed		Outcome †		POE Methods‡	Statistical metrics§	
		Green	Non-Green	Green	Non-Green	TC	IAQ		*p*	*d*
Brown et al (2010)	Canada	1	1	104	145		A	I		
Thatcher and Milner (2016)	South Africa	3	2	211	69		A	I	•	•
Thatcher and Milner (2012)	South Africa	1	1	161	79		A	I	•	
Thomas (2010)	Australia	1	-	238	-		A	I, II	•	•
Tham et al. (2015)	Singapore	1	1	32	33	A	A	I, III	•	•
Liang et al. (2014)	Taiwan	3	2	134	99	A	A	I, III	•	
Sediso and Lee (2016)	R.O. Korea	2	2	222*		A		I	•	
Pei et al. (2015)	China	10	42	500	500	A		I, III	•	
Gou and Lau. (2013)	China	1	-	182	-	A		I, III		
Gou et al. (2014)	China	9	5	774	477	B		I	•	•
Ravindu et al. (2015)	Sri Lanka	1	1	70*	-	B	B	I, III	•	
Paul and Taylor (2008)	Australia	1	2	40	53	B		I	•	
Collinge et al. (2014)	USA	1	-	48	-	B		I, II	•	
Altomonte and Schiavon (2013)	Global[a]	65	79	10,129	11,348	B	C	I	•	•
Menadue et al. (2014)	South Africa	4	4	600*	-	C		I, III	•	•
Leaman & Bordass (2007)	UK[b]	177	-	-	-	C	C	I	•	•

Notes:
† Study outcome: A = higher satisfaction in green buildings, B = lower satisfaction, and C = no difference found.
‡ POE methods covered: I = subjective assessment, II = energy performance, III = IEQ measurement.
§ Whether studies use inferential statistics in determining outcomes: p indicates use of p-value for significance testing and d a generic measure of effect size, most commonly Cohen's d.
* These studies do not explicitly provide per group sample sizes.
[a] Refers to data contained within the Centre of the Built Environment (CBE) database at the University of California, Berkeley, 63% of which come from industrialised countries.
[b] Data from the Building Use Studies (BUS).

3.5.2 Work performance and IEQ

In the literature, 'work performance' is also termed 'job performance', 'productivity', 'employee performance', and 'individual work performance'. Here we use 'work performance' as it is the most commonly used term. Work performance can be defined as a measure indicating how an employee is performing against the expected work tasks (Christiansen, Chandan and Global, 2017). It has been argued that level of work performance can vary according to the level of comfort with IEQ of workplace (Ali, Chua and Lim, 2015). Employees who are more satisfied with the conditions of their physical workplace are more motivated and achieve a better work performance (Leaman, 1995; Dole and Schroeder, 2001).

To test this, several studies have attempted to correlate work performance with different IEQ aspects, unfortunately, results across studies are contradictory (Table 3.3). Of the thirteen studies reviewed here, six studies focused on the effect of indoor air temperature on work performance (Nishihara, Yamamoto and Tanabe, 2002; Hedge, Sakr and Agarwal, 2005; Lan and Lian, 2009; de Korte *et al.*, 2015; Tanabe, Haneda and Nishihara, 2015; Maula *et al.*, 2016); three studied the effect of IAQ, ventilation and CO_2 levels (Wargocki *et al.*, 1999; Milton, Glencross and Walters, 2000; Federspiel *et al.*, 2004), and one study investigated the link between occupant comfort of overall IEQ and work performance metrics, such as absenteeism (Singh *et al.*, 2010). Some also cover other IEQ aspects such as noise (Witterseh, Wyon and Clausen, 2004), lighting (Fostervold and Nersveen, 2008; de Kort and Smolders, 2010) and control over workplace features (de Korte *et al.*, 2015).

As there is no single metric to assess work performance, the studies use a variety of subjective metrics (e.g., occupant satisfaction, self-appraisal), objective metrics (e.g., computerised tests) and secondary indicators (e.g., absenteeism and presenteeism). The studies in Table 3.3 are categorized into two groups according to their outcomes. Group A suggests a link between the investigated IEQ aspect and chosen work performance metric, while group B indicates no link. Outcomes are split across the two groups almost equally, though overall sample sizes in Group A are somewhat higher.

Six out of the thirteen reviewed studies are laboratory based (one additional study uses both laboratory and field data) and typically use computerised tests, often in controlled climate chambers over short periods (hours, or < 5 days), with small sample sizes (typically 20 – 60). Such studies can provide useful primary evidence through careful experimental design and allow for precise control of confounding and independent variables. This allows a cause-and-effect relationship to be established. However, the outcomes were contradictory in these studies as well, as only three out of six studies showed a link between work performance and IEQ aspects. Four out of the seven field studies use self-reported subjective metrics to measure work performance, while the remaining three use secondary objective metrics (e.g., absenteeism, tardiness) to measure work performance, but usually over short time periods (< 14 days/month).

In field studies, both subjective and objective data each have their limitations. For example, it is well-known that self-reported work performance is often inflated (Hoorens, 1993). Similarly, absenteeism as a secondary measure may mask the effect of other factors. For this reason, where possible, combined subjective and objective metrics are likely to provide a fuller picture of the effect of IEQ on work performance. Unfortunately, none of the studies in the literature use both metrics. Where time is a factor, i.e., there is an expectation that IEQ may change over time or it is necessary to observe temporal effects, work performance should be evaluated for a period long enough to detect changes in relation to changing IEQ; one month, at least, according to Kessler et al. (2007) (Kessler, Petukhova and McInnes, 2007).

Table 3.3 Summary of studies investigating the relationship between IEQ aspects and work performance in workplaces. †Study outcome: A = there was an effect and B = no effect was detected.

Study	IEQ parameter	Work performance metrics	Sample size	Study type	Study conclusion†
Singh et al. (2010)	Overall IEQ	perceived absenteeism and work hours.	263	Field	A
Tanabe et al. (2015)	Thermal satisfaction	Simulated office work: three-digit multiplication, proof reading, and creative thinking.	11	Field and Laboratory	A
Lan and Lian (2009)	Indoor air temperature	Computerized neurobehavioral tests.	21	Laboratory	A
Hedge et al. (2005)	Air temperature and relative humidity	Software estimated percentage of total keystrokes (correct + error keystrokes).	9	Field	A
Witterseh et al. (2004)	Noise	Self-estimated performance.	30	Laboratory	A
Wargocki et al. (1999)	Air quality	Simulated office work.	58	Laboratory	A
Milton et al. (2000)	Lower levels of outdoor air supply and IEQ complaints	Short term sick leave.	600	Field	A
Nishihara et al. (2002)	Thermal conditions	Computer tasks (Walter Reed Performance Assessment Battery test).	40	Laboratory	B
Fostervold and Nersveen (2008)	Type of lighting (direct or indirect)	The Digit Symbol subtest (WAIS-R).	64	Field	B
de Korte et al. (2015)	Control over lighting and	Standard reading task.	20	Laboratory	B

	air temperature				
de Kort and Smolders (2010)	Dynamic lighting	Days of sick leave.	140	Field	B
Maula et al. (2016)	Air temperature	Working memory, psychomotor performance during writing, and long-term memory.	33	Laboratory	B
Federspiel et al. (2004)	Ventilation rate	Talk tasks (length of call time).	119	Field	B

3.6 Aim of the research

The preceding review suggests that (i) the Middle East is unrepresented in the literature on green buildings despite their importance as depicted by the marked growth in energy consumption, (ii) existing research on the impact of IEQ on occupants in relation to green buildings is contradictory and relies primarily on subjective evaluation and (iii) there is insufficient field-data on work performance in relation to IEQ covering both subjective and objective metrics. To address these, we choose:

1. Jordan as a relevant example of the Middle East, e.g. the building sector represents approximately 33% of the total energy consumption in the country (Komendantova *et al.*, 2017), which is comparable to the rest of the Middle East at 28% (Nematollahi *et al.*, 2016).
2. LEED as the standard representing 'green buildings' in Jordan. To-date there are 21 registered[4] office buildings and 7 certified office buildings in the country, all adhering to the LEED standard (Ministry of Public Works and Housing, 2013).

We then perform a systematic field-evaluation of all certified LEED office buildings in Jordan, using comparable conventional "non-green" offices as control, to address the following research questions:

RQ 1. Do LEED office buildings in Jordan achieve the specified minimum IEQ standards in terms of thermal conditions and indoor air quality, after hand over?

RQ 2. Are employees of LEED office buildings in Jordan more satisfied with the quality of their indoor environment compared to employees in conventional offices, and do these correspond with the observed differences in IEQ, if any?

[4] A LEED registered building achieves some of LEED requirements without attaining the minimum required score (40 points) to be classified as LEED-certified, hence the building can be only registered with USGBC without green certification level.

RQ 3. Do employees in LEED office buildings in Jordan demonstrate better work performance compared to employees in conventional buildings, when measured using both subjective and objective metrics?

3.7 Methods

Of the three methodological aspects discussed in Section 3.5.1, this study uses Aspects I and III to answer the research questions. Aspect I, i.e., subjective assessment of occupant satisfaction with IEQ and their work performance is supported by in-depth interviews to collect further information of investigated buildings to better understand the context. Absenteeism and presenteeism are also measured as secondary indicators of work performance. Aspect III i.e., objective assessments, co-incident with Aspect I, covered thermal conditions (T_a, T_r, RH, and V_a) and indoor CO_2 concentration levels as an indicator of IAQ (ASTM D6245-18, 2018). We do not use Aspect II because assessment of energy use is not part of our research questions. As our interest is in the potential difference in response of particular metrics (from Aspect I and Aspect III) between two or more groups (i.e. different types of buildings), we use a between-subjects experimental protocol (Miller, 1984). The next sections detail building selection, occupant recruitment, methods for objective and subjective data collection, and analysis.

3.7.1 Building selection

The total number of LEED-certified office buildings in Jordan is currently seven. The buildings are owner-occupied and belong to organisations whose overall size is in the fourth quartile (by number of full-time employees) (Ministry of Public Works and Housing, 2013).To match these, we targeted organizations with a conventional office building (hereafter referred to as CB) located within the same urban context of the LEED buildings, with at least 40 full-time employees with similar job roles to those in LEED buildings. Recruitment of buildings for the study was achieved through an invitation letter, explaining the research idea and objectives, sent to senior management of 33 CBs and all 7 LEED buildings. Five out of the seven LEED buildings agreed to participate (5:7, 71%) along with eight CBs (8:33, 24%), bringing the total to 13 office buildings. The two remaining LEED buildings cited building security criteria as the key reason for not being able to participate. All buildings are in Amman, north-central Jordan, and they match the same climate conditions, long hot summer and short cold winter. The relative humidity is around 70% in winter and between 30% – 40% in summer (DOS, 2016).

A contact person, usually a middle manager, was appointed by each participating organisation to discuss the process of conducting the fieldwork. All eight CBs agreed to surveys being administered to their employees, while only five agreed to conduct on-site measurements. The participating LEED buildings confirmed all the research aspects. The data were collected from these buildings during three data collection campaigns spread over two years between Jul 2017 – Feb 2019 (Figure 3.1). Details of the participating buildings can be seen in Table 3.4. All the buildings in our study are classed as "offices" with occupants undertaking similar job roles varying between clerical, design, administrative, and management (Figure 3.2 and Figure 3.3)

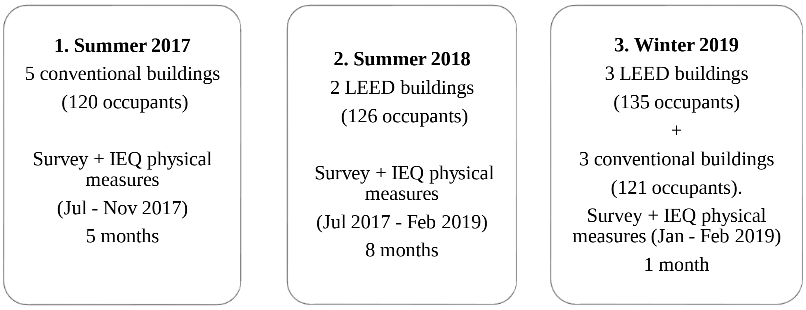

Figure 3.1 Overview of research data collection (July 2017 – February 2019; $n_{buildings} = 13; n_{occupants} = 502$).

Table 3.4 Comparison of LEED and conventional building (CB) characteristics.

Item	LEED	CB
Construction age range	2010 – 2019	2000 – 2019
TFA (m^2)	9,000 – 15,000 m^2 (including car parking, gathering areas, meeting rooms, cafeteria, and sport facilities). Estimated "office only" TFA range is: 1650 – 2000 m^2.	700 – 1500 $m^{2.}$
Workplace layout	85% of respondents work in open-plan workplaces and only 15% had private offices.	56% of respondents had open plan workplace and 44% had their own private offices.
Employment area (m^2)	4 m^2/person in open plan. 12 m^2/person in private offices.	4 m^2/person in open plan. 10 m^2/person in private offices.
Total number of employees	50 – 120	40 – 50
Number of floors	8 – 14	2 – 5

Ventilation	Active ventilation systems, designed to achieve 8.5 l/s/person.	Concurrent mixed-mode ventilation (active cooling between May – October, while active heating during December, January, and February, buildings natural ventilation in March, April, and November by open/close windows to regulate the internal air temperature.
Lighting	Artificial and natural lighting (occupancy and illuminance sensors).	Artificial and natural lighting (occupants have full control over lighting).
Windows	Fixed double-glazed facades.	Evenly distributed operable windows.
Other features	Walls were painted with Volatile Organic Compound (VOCS) free paint and floors covered with carpet to eliminate indoor air pollutants.	-
LEED certification category	1 x LEED-Silver. 3 x LEED-Gold. 1 x LEED- Platinum.	-

Figure 3.2 Examples of buildings in this study.

Figure 3.3 Selected workplaces in the study (examples a–b from conventional building, c–d from LEED).

3.7.2 Occupant recruitment

As the maximum number of employees across the recruited offices was 120, all employees in all organisations were invited to participate in the research through a leaflet that explained the overall aim of the research, data privacy procedures, and the need for prior informed consent. This resulted in an overall return rate of 53.5% (241/450) in CBs and 65.2% (261/400) in LEED buildings. A complete socio-demographic breakdown split by building type can be seen in section (3.11.a), which is available in the Electronic Supplementary Material (ESM) in the online version of this paper.

We observe that job categories, working experience, daily working hours, education level and monthly earnings are broadly comparable across the building types. However, we observe systematic differences in gender distribution (39% and 49% females in CB and LEED, respectively) and the number of people per office (a majority of 1 – 4 people per office in CB compared to 10 – 24 in LEED). Both are representative of the respective distributions in each building type, i.e., fewer females and cellular offices in the eight CB buildings surveyed.

3.7.3 Objective measurements

To address RQ1 and the latter half of RQ2, continuous on-site monitoring of T_a, RH, and CO_2 was conducted in the investigated buildings (Table 3.5) (Elnaklah, Fosas and Natarajan, 2020). Continuous measurements were undertaken using Raspberry-Pi-based sensors that have undergone rigorous testing and calibration, making them suitable for obtaining time series with good accuracy (Lovett *et al.*, 2016; Vellei *et al.*, 2016). Monitored buildings were provided with 83 Raspberry-Pi to monitor air temperature and relative humidity, and 21 Raspberry-Pi to monitor CO_2 (Figure 3.4)

Indoor sampling positions were selected based on four coverage criteria (i) areas with both high and low density, (ii) areas experiencing any occupant complaints or discomfort, (iii) different floors of the buildings, and (iv) sampling criteria for CO_2 concentration is one per 500 m^2 for buildings with total floor area less than 3000 m^2 (Region, 2019).

In LEED buildings, a majority of sensors were located in the open plan workplaces, as these were the most common type of occupied area within the buildings. While in CBs, sensors were located in both open plan workplaces and cellular offices. All sensors were placed on employees' desks at heights varying between 0.70 – 0.90 m from floor level and away from local heat sources (e.g., heaters, windows, and PC monitors). The date and time were setup according to the local time in Jordan. All sensors were identified with a label showing the serial number and building name. Employees were asked not to cover, touch or unplug the sensors from power. The data were logged at 5-minute intervals and downloaded on a weekly basis during the monitored periods.

In addition to continuous measurements, periodic spot measurements which complied with EN ISO 7730 (ISO 7730, 2005) and ISO 7726 (EN ISO 7726, 2001)were undertaken in the investigated buildings to assist in evaluating the occupants' thermal comfort and calculate the predicted mean vote (PMV) (ANSI/ASHRAE 55, 2017; d'Ambrosio Alfano *et al.*, 2020). The spot measurements covered four physical indicators: T_a, T_r, RH, and V_a

for which readings were taken simultaneously to the time of the survey using the HD 32.3 kit (Delta OHM, 2019). In addition, two other indicators were assessed to help in calculating the PMV, clothing thermal insulation (clo) and metabolic rate (met).

All the investigated buildings in our study are offices and their occupants involved in typical sedentary work activities (e.g., reading, writing, computer typing) with occasional walking between workstations for document delivery or communication. This is expected to entail a light metabolic rate between 1.1 and 1.3 met (EN ISO 8996, 2004; ANSI/ASHRAE 55, 2017). As the monitoring campaigns were conducted in both summer and winter, occupant clothing insulation levels ranged between 0.9 and 1.4 clo (EN ISO 9920, 2009; ANSI/ASHRAE 55, 2017).

Further, local discomfort was assessed during the spot measurements, and no significant local discomfort sources were detected, thus we assume that the Raspberry-Pi devices reflect the actual performance of the building in terms of air temperature and relative humidity. Technical specification of our instruments is provided in (3.11.a), which is available in the Electronic Supplementary Material (ESM) in the online version of this paper.

Table 3.5 Number and location of sampling points for continuous monitoring using Raspberry-Pi devices (F = floor, CB = conventional building).

Building	Sensor type		Location	Monitoring period		Total continuous days
	T_a + RH	CO_2		Months	Year/s	
LEED1	3	2	F2, F3	Jan – Feb	2019	30 (T_a + RH + CO_2)
LEED2	3	2	F2, F3			
LEED3	3	2	F2, F3			
LEED4	5	2	F1, F2, F3	Jul – Feb	2018 - 19	240 (T_a + RH + CO_2)
LEED5	35	3	F1, F2, F3, F4			
CB1	8	2	F1, F2			
CB2	8	2	F2, F3			
CB3	8	2	F1, F2	Jul – Nov	2017	150 (T_a + RH + CO_2)
CB4	5	2	F1			
CB5	5	2	F1			

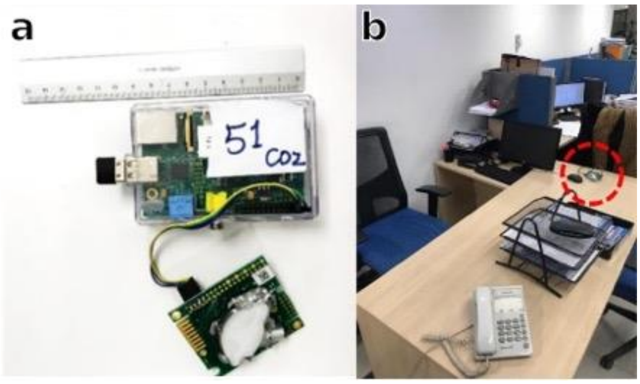

Figure 3.4 Raspberry-Pi based CO_2 logger in the study (‘a’ logger; ‘b’ example of logger location on employee’s desk).

3.7.4 Subjective measurements

Here, we describe first, the overall process, and then the details and sources used, to design the questionnaire to help address RQ2 and RQ3. Initial discussions with the various gatekeepers suggested that the most effective means to obtain high return rates would entail a paper-based questionnaire, completed with researcher assistance.

The questionnaire contained both English and Arabic text, as most participants’ first language is Arabic. The English version of the questionnaire was translated into Arabic by a ‘sworn translator’ who has a high level of education and experience. The translated version of the questionnaire was tested before starting the study by sending it to five university students fluent in both Arabic and English. Based on their suggestions, minor refinements such as deletion of overlapping terms were made. The English originals were retained alongside the Arabic translations in the final questionnaire.

Survey respondents were provided with an introductory session (5 – 7 minutes) by the researcher to explain the research idea and objectives, and that all responses will be anonymised and not directly shared with gatekeepers. Prior informed consent was obtained following well-established university ethics procedures. Pilot tests suggested an average survey completion time of 5 minutes, which was borne out during data collection.

The questionnaire comprises three sections. The first section contains six socio-demographic questions covering gender, job role, work experience, salary, number of daily working hours and workplace layout. The second and third sections, described below, were designed to evaluate occupant perception of IEQ and work performance respectively.

Occupant satisfaction with IEQ: This section was based on two well-established workplace surveys (WGBC, 2014): the Building Use Studies survey (Methodology, no date) and the Occupant Indoor Environmental Quality Survey by CBE, Berkley (CBE, 2019). Four key IEQ parameters were interrogated: indoor air quality and ventilation, noise, lighting, and thermal comfort, with each aspect covered using 2 – 5 questions that had three types:

- Satisfaction rating of IEQ items on a seven Point-Likert scale going from dissatisfied (-3) to satisfied (+3), where 0 represents a neutral or no opinion.
- Each of the previous questions was followed with a question asking respondents to rate if a particular IEQ aspect affect the work performance negatively on a seven-point scale from ‘not a significant negative effect’ (1) to a ‘significant negative effect’ (7).
- Open-ended question to allow respondents the freedom to provide more detailed responses and raise any specific problem that is not covered in the survey.
- In addition, Thermal Sensation Vote (TSV) and Thermal Preference Vote (TPV) of occupants were assessed using the widely used ASHRAE 55 seven points scale (ANSI/ASHRAE 55, 2017).

Work performance: Based on Singh et al. (2010) and Milton et al. (2000), we use absenteeism and presenteeism as key indicators of work performance. While other, more direct measures, such as computerized neurobehavioral tests, standard reading task, memory task, and different simulated office tasks were adopted in the literature, these were considered inappropriate for our study due to being too intrusive or not repeatable at-scale in a real working environment.

Absenteeism can be defined as the average number of employee days lost per year through illness and unauthorized absences as a percentage of contracted days (IFC, 2017). While presenteeism can be defined as being not fully functioning at work because of health issues (WGBC, 2014). Chua et al. (2016) found in their study that the high level of employee absenteeism could be viewed as an indicator of poor work performance, and the highly motivated and comfortable employees take 37% fewer sick leaves.

We assess absenteeism and presenteeism using the short version of the Health and Work Performance Questionnaire (WHO HPQ), developed by the World Health Organization (WHO). This questionnaire is well-established in the literature and is considered both valid and reliable (Kessler, Petukhova and McInnes, 2007; de Kort and Smolders, 2010; Pournik *et al.*, 2012). For both absenteeism and presenteeism one may use either the preceding 7 days or 4 weeks, but we use both as an inter-metric reliability check. The absenteeism section consists of 8 questions covering:

- The total number of working hours in the last 7-day (and the last 4-week) prior to the survey date.
- The number of missed workdays due to illness or other reasons (including vacations).
- Number of days – miss part of working day – due to physical / mental health issues or other reasons.
- Number of days when they came early to work, or went home late, or worked on their day off.
- The expected total working hours by employer in a typical 7-day week.

The monthly Absolute Absenteeism (A_A, hours) is then calculated as (Kessler, Petukhova and McInnes, 2007) :

$$A_A = 4 \times \mathrm{B4} - \mathrm{B6} \tag{2}$$

where B4 represents the number of expected working hours by employer in a typical 7-day week, and B6 is the number of hours that employee worked in the past 4 weeks. Similarly, monthly Relative Absenteeism (A_R) is computed as:

$$A_R = \frac{4 \times \mathrm{B4} - \mathrm{B6}}{4 \times \mathrm{B4}} \tag{3}$$

where A_R is a percentage ranging between a negative number (i.e., the employee worked more than the expected working hours), 1 (indicates employee was always absent during the last 4 weeks) and 0 (indicates employee work as expected).

Turning to the presenteeism section, it consists of three questions asking employees to evaluate their work performance on a scale from 0 to 10 (where 0 is the worst performance and 10 is the top performance). These ask employees to:

- Rank their work performance according to most workers in a similar job.
- Evaluate their work performance during the last year.
- Evaluate their work performance in the period of 4 weeks prior to the survey date.

In this section, the absolute and relative presenteeism were measured to provide better understanding of employee work performance for 4 weeks. The Absolute Presenteeism (P_A, %) was calculated as:

$$P_A = 10 \times \mathrm{B11} \tag{4}$$

where B11 is the self-assessed score of work performance in the last 4 weeks. P_A is an integer score between 0 (total lack performance during working hours) and 100 (no lack of performance during working hours). Relative Presenteeism (P_R) is calculated as:

$$P_R = \frac{\mathrm{B11}}{\mathrm{B9}} \tag{5}$$

where B9 is the self-reported score of work performance compared to other employees working in a similar job. P_R ranges between 0.25 (indicating the employee worked 25% or less than other workers), and 2 (indicating that the employee worked 200% more than other workers).

For example, if respondent rates his own performance as 1, and the average worker's performance at 8, he is assigned a presenteeism score of 0.25 (1 divided by 8 is 0.125, restricted to the lower bound of 0.25). This means, that respondents' work performance was as low as one-fourth the average. If another respondent rates his performance at 9, but rates the average worker's performance at 3, he gets the score of 2 (9 divided by 3 is 3, restricted to upper bound of 2). This means, that respondent has more than twice the work performance of the average worker.

In addition to the questionnaires, 15 semi-structured interviews with the buildings' owners, managers, designers, and operators were conducted between July 2017 – Feb 2019. Each interview took approximately 60 – 90 minutes. The data generated by the interviews were documented using handwritten notes. These interviews had three themes:

- Motivations to implement green design and basic data (e.g., total floor area of building, building age, total number of employees).

- Details of green features (e.g., green certification level, Heating, Ventilation and Air-Conditioning system (HVAC), and lighting).
- Architectural and structural details.

3.7.5 Analysis methods

Classical hypothesis testing is used to analyse potential differences in the performance of conventional and LEED buildings in the study. When the response variable is numerical and continuous over an interval, like the case of CO_2 concentration in part-per-million (ppm), the *t*-test is used to test the null hypothesis that there is no difference in the mean response between the two groups, which assumes that samples follow a normal distribution. In particular, Welch's unequal variances *t*-test is used as the number of samples or their variances are not necessarily equal, as seen in the next section. Confidence intervals are reported together with the differences between groups and the effect size is reported using Cohen's d metric,

$$d = \frac{\mu_a - \mu_b}{s} \tag{6}$$

where μ_a represents the sample mean in one group, μ_b the mean of the other sample and s the pooled variance of the samples (Cohen, 1988).

Other response variables follow a categorical or ordinal scale, like satisfaction scores on a 7-point Likert item (Garland, 1991). For these cases, the non-parametric Kruskal-Wallis H test is used to test the null hypothesis that there is no difference in the median response between the two groups, under the assumption that the samples of the two groups follow the same distribution.

Effect sizes are reported using the Rank Biserial Correlation (RBC) (Cureton, 1958), a measure of how disaggregated the ranks of two groups a and b are. Values of RBC range between -1 to 1: values of 0 mean that the ranks are similar between the two groups and values of -1 and 1 that the ranks of one group are all below those of the other (the sign depends on which of the two groups is taken as the reference). For thermal comfort data, the TSVs were compared to the ASHRAE 55 comfortable range of [-1, +1] (ANSI/ASHRAE 55, 2017), and PMVs were compared to ISO 7730 comfort range of [-0.5, +0.5] (ISO 7730, 2005), then a comparison between TSVs and PMVs was conducted in both buildings types.

The analysis considers only questionnaires with responses to every question. However, in the case of absenteeism and presenteeism, data were cleaned according to WHO guidelines (Kessler, Petukhova and McInnes, 2007). This section of the questionnaire requires users to give thoughtful numerical responses about their working hours. The standard questions include pre-quest, i.e., questions that are not included in the analysis but that help respondents give better estimates on a following question.

The pre-quest allows superficial responses to the hours worked in the last 28 days to be estimated. Aligning with WHO guidelines, a rational imputation of the data is made for large differences between the estimated hours the occupant worked in the last 28 days and the reported ones based on the 90th percentile. This reduced the dataset from 502 total responses to 452 (i.e., from 261/241 responses in LEED/CB to 228/224). The analysis was done using (i) Python (Python Software Foundation, 2020), including Numpy (Oliphant, 2006; Walt, Colbert and Varoquaux, 2011), Pandas (McKinney, 2010) and Pingouin (Vallat, 2018) libraries, and (ii) R (R Core Team, 2019), including the Tidyverse family (Wickham *et al.*, 2019) and HH libraries (Heiberger and Robbins, 2014).

3.8 Results and discussion

This section presents the results from the objective measures of thermal conditions (T_a, T_r, RH, and V_a), and IAQ (CO_2 concentration levels) (see Aspect III in Section 3.5.1), and the result of subjective measures including occupant satisfaction with IEQ and work performance (absenteeism and presenteeism) (see Aspect I in Section 3.5.1). As we are interested in occupant perception during working hours, data between 0900 and 1700 from Sunday to Thursday were extracted and analysed based on the typical working time in Jordan (Friday and Saturday being the weekend). Thermal comfort conditions and CO_2 data were compared to both the recommended standards LEED /ASHRAE 55 and LEED /ASHRAE 62.1 respectively, and across building groups.

3.8.1 IAQ

Taking the CO_2 concentration as a proxy for indoor air quality, two complementary aspects were studied. Firstly, mean CO_2 concentration levels were compared according to the building type, and secondly, the average fraction of the day within the LEED limit of 1,100 ppm was appraised (Figure 3.5) (ANSI/ASHRAE 62.1, 2010). For average CO_2

concentration levels, Welch's unequal variances *t*-test suggests that the null hypothesis of equal means between CBs (μ=587.23, s =219.54, n=3223) and LEED (μ=655.96, s =198.67, n=1576) buildings can be rejected ($t(3421) = -10.87, p - value < 10^{-4}$; $\Delta\mu_{LEED-CB} = +68.73$; 95% CI $[56.33, 81.13]$; $d = 0.32$). Although statistically significant, the effect size is small, and the difference is negligible in practical terms since both means are well under the upper limit of 1,100 ppm, even though LEED has a marginally higher concentration.

This characterization contrasts with the second test for the average fraction of the day within design limits. Here, the test suggests that the null hypothesis of equal means between CBs (μ=95.85, σ=3.35, n=31) and LEED (μ=98.26, σ=3.67, n=31) buildings, can be rejected ($t(60) = -2.71, p - value < 10^{-2}$; $\Delta\mu_{LEED-CB} = +2.41$; 95% CI $[0.63, 4.20]$; $d = 0.65$). These results show how LEED buildings deliver an environment that is more often within the design specification despite the marginally higher CO_2 concentration levels, with a moderate effect size.

This variation is judged to be attributable to the different design approaches of ventilation in these buildings. LEED buildings are designed to be airtight to reduce energy consumption and use controlled HVAC systems, while the CBs used mixed-mode ventilation that depends on wind and stack effect and occupant behaviour of window opening to deliver fresh air.

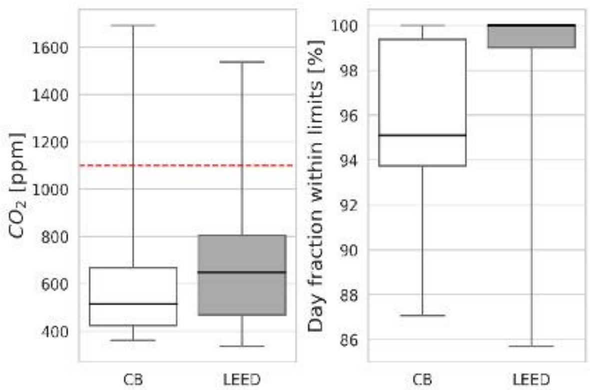

Figure 3.5 CO_2 concentration according to building type using continuous measurements filtered to occupied hours [0900, 1700] between July 2017 and February 2019—see Section 3.8.1; sample size conventional: 3223 hours in 5 buildings; sample size in LEED: 1576 hours in 5 buildings; whiskers indicate minimum and maximum readings; dashed line indicates upper acceptable limit at 1100 ppm according to ASHRAE 62.1.

3.8.2 Thermal conditions and comfort

Figure 3.6 compares the self-reported TSVs and the calculated PMVs using Fanger's model in ASHRAE 55 and ISO 7730 in the CBs and LEED buildings, and Table 3.6 illustrates the thermal acceptability percentages of TSVs, TPVs and PMVs[5]. In CBs, only 73% of the TSVs were within [-1, +1], hence failing the 80% ASHRAE 55 acceptability threshold. This is consistent with the PMV prediction of neutral to slightly warm and 71% predicted to fall within ISO 7730 recommended PMV range of [-0.5, +0.5]. In LEED buildings, 85% of TSVs fell within the ASHRAE 55 acceptable comfort zone, which aligns with the PMV prediction of 85%. An analysis of spot measurements of thermal conditions reveals that dry bulb temperature and mean radiant temperature are almost identical (difference of 0.18 ± 0.36 °C, R^2 = 0.97), this is consistent with other studies in the literature (Walikewitz *et al.*, 2015; Hughes and Natarajan, 2019).

[5] Note TSV and TPV are ordinal due to survey design whereas PMV is continuous within the range. Hence, observations will refer to integer values whereas predictions and standards may contain non-integer values.

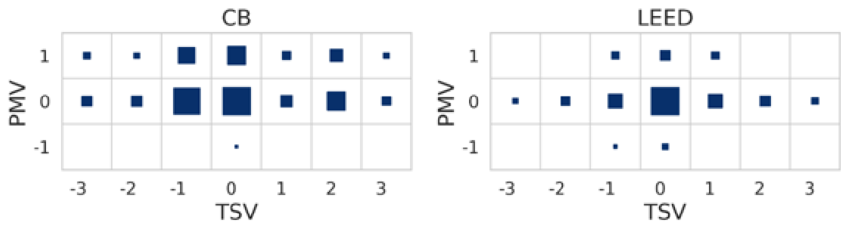

Figure 3.6 Comparison of TSV as reported by occupants and PMV as predicted by Fanger model in ISO 7730 (2005). PMV data calculated using spot measurements. The plot shows squares proportional to the number of vote counts only used categories, which vary according to building type. Cases without votes are empty; Conventional Buildings (CB, n_samples=241, minimum count = 1, maximum count = 57); (LEED, n_samples=261, minimum count = 1, maximum count = 123).

Table 3.6 Thermal acceptability percentage for both subjective and objective measurements; CB indicates conventional building. PMV calculated from spot measurements. Note that the standard specifies a comfort range for PMV [− 0.5, +0.5], whereas survey data are ordinal and are hence presented within [−1, +1]. For comparison, we present PMV data within both ranges .

Bldg. Type	TSV (M ± SD)	PMV (M ± SD)	$-1 \leq TSV \leq +1$	$-0.5 \leq PMV \leq +0.5$	$-1 \leq PMV \leq +1$	$-1 \leq TPV \leq +1$
CBs	-0.1 ± 1.3	0.3 ± 0.4	73%	71%	95%	88%
LEED	0.0 ± 1.0	0.3 ± 0.3	85%	85%	98%	88%

We illustrate prevailing indoor conditions in Figure 3.7 and Figure 3.8 based on the time series for air temperature and relative humidity obtained with the Raspberry-Pi devices for both CBs and LEED buildings. These alone cannot be used to quantify the percentage of time that indoor environments meet requirements in ASHRAE 55 of PMV votes in the range of [-0.5, +0.5], because Fanger's model also requires mean radiant temperature, air velocity, occupant clothing and occupant metabolic rate.

However, data collected as part of the questionnaires and spot measurements reveal that, besides air and radiant temperatures being almost identical, there is little variation in observed values for air velocity, clothing, and metabolic rates. Considering that spot measurements were taken at different times of the year, a reasonable assumption can be made that these values are representative over the continuous measurement periods.

Hence, we can estimate the percentage of occupied hours indoor thermal conditions are within the recommended ASHRAE 55 ranges using the mean and standard deviation of these variables. We estimate that between 1% and 36% of the data points in the CBs (Figure 3.7) fall within the ASHRAE 55 recommended range during working hours, in contrast to the range between 49% and 69% for the LEED buildings (Figure 3.8). Despite the uncertainty in the ranges obtained, this suggests better standard compliance in the LEED buildings.

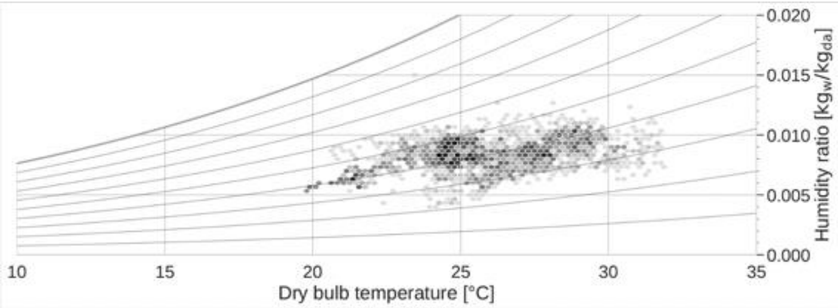

Figure 3.7 Psychometric chart for conventional buildings in the study using continuous measurement data filtered to occupied hours [0900, 1700] between July 2017 and November 2018 — see section 3.8.2; sample size of 560 hours in 5 conventional buildings; hexagons shade proportional to number of samples.

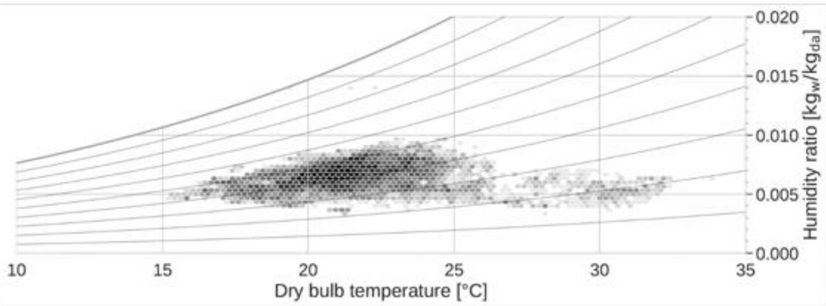

Figure 3.8 Psychometric chart for LEED buildings using continuous measurement data filtered to occupied hours [0900, 1700] between Jul 2018 and February 2019 — see section 3.8.2; sample size of 912 hours in 5 LEED buildings; hexagons shade proportional to number of samples.

3.8.3 Occupants' satisfaction of IEQ

Figure 3.9 shows the median, first and third quartile of occupant satisfaction with the LEED and CBs in four IEQ aspects: IAQ and ventilation, noise, lighting, and thermal comfort. Surprisingly, this suggests that the occupants of LEED buildings had a lower median score of satisfaction for all investigated IEQ parameters except noise. This finding was supported with the results of the Kruskal-Wallis H test, which suggests rejecting the null hypothesis of no difference between median response according to the building type for the IAQ and ventilation, noise and thermal comfort (p-value < 0.05), while it failed to reject differences for lighting (Table 3.7).

Further, differences between the median scores of satisfaction achieved for eight individual aspects related to the IEQ were investigated (Table 3.7 and Figure 3.10). Interestingly, occupants in LEED buildings had lower satisfaction compared to their counterparts in CBs in overall IAQ, fresh air, ventilation, sun glare, and air temperature where the differences in the median scores of occupants' votes on 7-point scale were (2, 1, 1, 1, 1) respectively.

LEED buildings' occupants were more satisfied with the noise levels with a difference in median scores of -1, similar to Liang et al. (2014). To compare the obtained results to other studies' findings, the differences in mean scores of occupants' satisfaction towards the investigated IEQ parameters were computed. The obtained mean differences ranged between 0.22 – 0.60 and can be considered high when compared it to the literature. For example, Altomonte and Schiavon (2013) and Paul and Taylor (2008) report differences in mean scores ranging between 0.001 – 0.22.

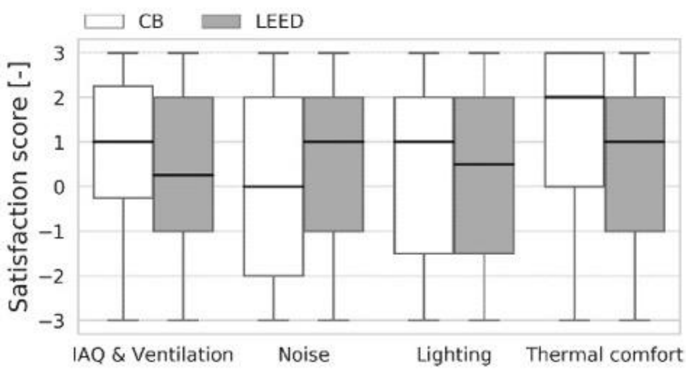

Figure 3.9 Occupant satisfaction with four IEQ aspects (sample sizes: 241 respondents in conventional buildings (CB), 261 respondents in LEED buildings; satisfaction score from dissatisfied (−3) to satisfied (3); whiskers indicate minimum and maximum scores).

Table 3.7 Statistical analysis of differences in median statistics from the surveys, according to building type and IEQ aspects (H indicates Kruskal-Wallis H statistic; * indicates statistically significant results at 95% confidence level; RBC is the rank biserial correlation); CB indicates conventional building. Numbers in the CB and LEED columns represent responses on their respective scales in the survey.

Case	Reference	CB	LEED	*H*	*p*-value	RBC
Overall satisfaction	Figure 3.9					
IAQ & Ventilation		1	0.25	14.79	<10-3*	-0.20
Noise		0	1	4.68	0.03*	0.11
Lighting		1	0.5	1.98	0.15	-0.07
Thermal comfort		2	1	12.18	<10-3*	-0.18
Individual questions	Figure 3.10					
Air quality		2	0	16.78	<10-3*	-0.21
Fresh air		1	0	18.29	<10-3*	-0.22
Air humidity		1	1	3.44	0.06	-0.09
Overall ventilation		1	0	11.50	<10-3*	-0.17
Background noise		0	1	4.68	0.03*	0.11
Natural light		2	1	0.10	0.75	-0.02
Sun glare		1	0	4.99	0.03*	-0.11
Air temperature		2	1	12.18	<10-3*	-0.18
Work performance	Figure 3.11					
Quality of air		-1	0	1.68	0.19	0.07
Distraction from noise		0	0	0.21	0.64	-0.02
Quality of light		-1	-1	2.21	0.14	0.08
Temperature		0	0	2.40	0.12	-0.08
Absenteeism	Figure 3.12					
Absolute	Eq. (2)	4	0	4.22	0.04*	0.11
Relative	Eq. (3)	0.02	0	4.46	0.03*	0.12
Presenteeism	Figure 3.13					
Absolute	Eq. (4)	80	90	1.59	0.21	-0.07
Relative	Eq. (5)	1.14	1.13	0.25	0.62	0.03

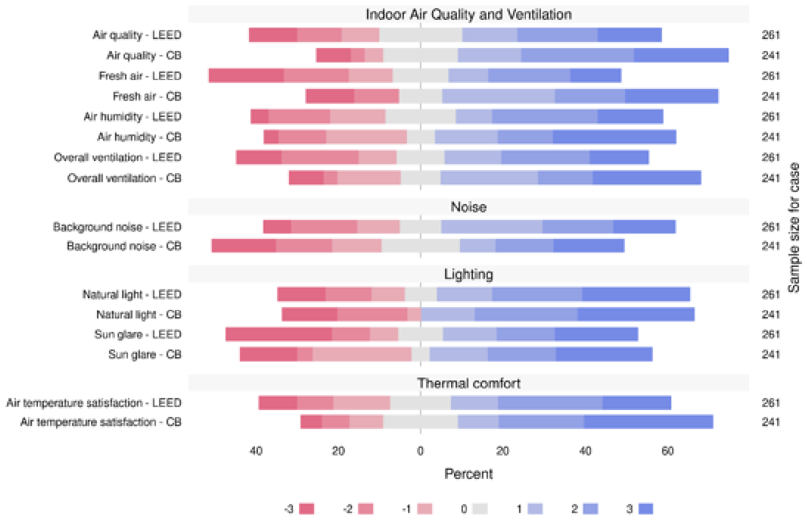

Figure 3.10 Occupant satisfaction in IEQ categories according to building type . CB indicates “conventional building”, LEED indicates “LEED building”; the scores span from dissatisfied (−3) to satisfied (3), and (0) no opinion. To enable interpretation, the x-axis has been mapped such that “0%” maps to “0” on the survey scale. Numbers on either side of “0%” can be used to judge the percentage of responses in each of the three categories below and above “0” on the survey scale.

The perceived IEQ results related to thermal comfort show that there are statistically significant differences between CBs and LEED buildings, but that the effect size is moderate (Table 3.7). This seems to challenge findings in the previous sections (3.8.2), where both building types shown to have satisfactory indoor environments for their occupants based on TSVs, TPVs and PMVs (Table 3.6). This could be explained considering Figure 3.10, which shows that the main differences between CBs and LEED buildings are in the proportion of votes in the extreme categories of the satisfaction scale. Further, although the ventilation systems in the LEED buildings were designed based on the LEED requirements (8.5 L/(s.person)) and the physical measurements of CO_2 showed a compliance with LEED specification (ANSI/ASHRAE 62.1, 2010), surprisingly only 48% of the respondents were satisfied with the overall IAQ and ventilation compared to 66% in CBs (Figure 3.10). One possible explanation reported in the literature that ventilation rates below (10 L/(s.person)) in buildings can cause lower perceived IAQ (Rashid and Zimring, 2008). Ravindu et al. (2015) also show that occupants in a LEED-platinum building in Sri Lanka had lower satisfaction with ventilation compared to the control group.

Figure 3.11 shows the occupants' responses of which IEQ parameter of the four investigated parameters (IAQ and ventilation, noise, lighting, and indoor air temperature) has a significant negative effect on their work performance. We observe that the percentage of occupants whose work performance was negatively affected by IAQ, noise, and lighting was higher in the LEED buildings compared to the CBs, while occupants' work performance in CBs was negatively affected by air temperature. However, this finding was not statistically significant, as the Kruskal-Wallis test fails to reject the null hypothesis of no difference between median responses according to building type for all four aspects (p-value > 0.05, Table 3.7).

Table 3.8 shows the results of respondents' perception of the most IEQ parameters that they judged to need improvement. The air temperature was the main concern for 43% of respondents in CBs, while the ventilation was the major concern for 34% of respondents in LEED buildings, a finding that is supported across other studies in the literature (Roelofsen, 2002; Paul and Taylor, 2008). According to 24% of respondents, the air temperature in LEED buildings needs to be improved. Lighting was seen to need improvement by only 8% and 12% of occupants in CBs and LEED respectively, while noise was not perceived as a problem in both building types.

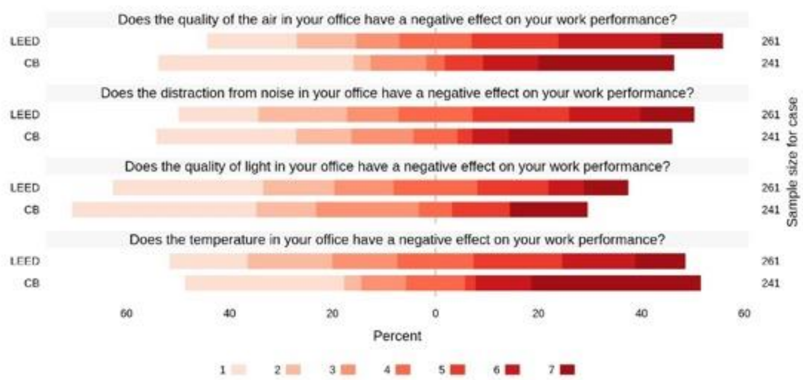

Figure 3.11 Effect of four IEQ aspects on occupant work performance. CB indicates "conventional building", LEED indicates "LEED building"; the scores span from not a significant negative effect (1) to a significant negative effect (7), and no opinion (4). To enable interpretation, the x-axis has been mapped

such that “0%” maps to “4” on the survey scale. Numbers on either side of “0%” can be used to judge the percentage of responses in each of the three categories below and above “4” on the survey scale.

Table 3.8 Top 5 physical items occupants would like to change in their work places according to the building type (sample sizes: 241 respondents in conventional buildings (CB), 261 respondents in LEED buildings; N.B. multiple choices were allowed per occupant— columns do not add to 100%).

Rank	CB	%	LEED	%
1	Air temperature	43	Ventilation	34
2	Layout	29	Nothing	30
3	Ventilation	18	Temperature	24
4	Lighting	8	Lighting	12
5	Nothing	8	Layout	7

3.8.4 Absenteeism and presenteeism

The 4-week estimation revealed a small difference in the absolute and relative absenteeism of respondents according to the building type (Figure 3.12), for which the Kruskal-Wallis test suggests rejecting the null hypothesis (Table 3.7). CBs respondents had 4 hours of absolute absenteeism per month and 0.02% of relative absenteeism. This is expected to result in a loss of 48h of the expected working hours per year, which means losing around 300 JD (≈ 425 USD) of annual operation cost due to absenteeism if we consider a yearly income level of about 12,000 JD (≈ 16,900 USD); hence a negligible effect.

Turning now to presenteeism, there is no significant difference in both absolute and relative presenteeism between respondents of LEED and CBs (Figure 3.13), as the Kruskal-Wallis test fails to reject the null hypothesis (Table 3.7). Respondents in both building types do not report any lack of performance during time on the job during a 4-week period. The respondents in CBs and LEED buildings rated their work performance at 114% better than employees working in a similar job to their jobs. This can be understood through the well-known phenomenon of illusory superiority, which is a condition of cognitive bias that refers to the tendency that people overrate their performance above the average or above the performance of other people (Hoorens, 1993).

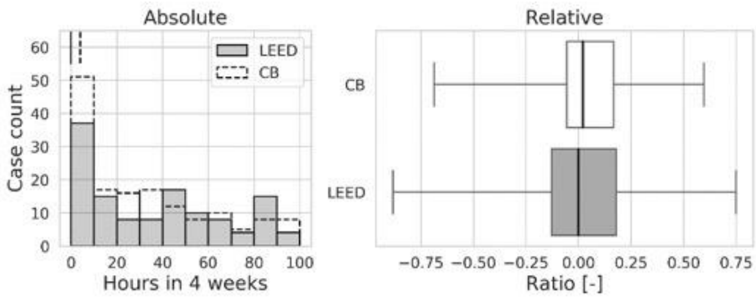

Figure 3.12 Absenteeism scores (see Eqs. (2) and (3) for absolute and relative scores , respectively; floating segments indicate group median; positive values indicate absenteeism while negative ones overwork; whiskers indicate minimum and maximum values. Sample sizes: 224 respondents in conventional buildings (CB), 228 respondents in LEED buildings).

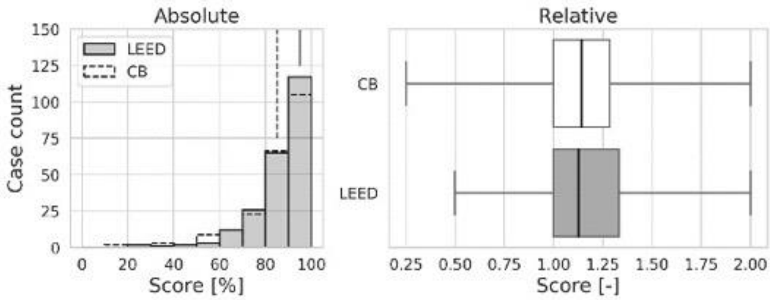

Figure 3.13 Presenteeism scores (see Eqs. (4) and (5) for absolute and relative scores , respectively; floating segments indicate group median; boxplot whiskers indicate minimum and maximum values. Sample sizes: 224 respondents in conventional buildings (CB), 228 respondents in LEED buildings).

3.9 Conclusions

One of the main unresolved challenges for the building industry is to truly understand how occupants perceive the buildings they occupy, feeding these lessons back into the design and operation process. Although there is a growing database of building use studies, the Middle East is highly under-represented, with no study of IEQ performance in the region. Hence, this is the first study to evaluate the IEQ performance in office buildings in the Middle East.

Using Jordan as a representative example of the Middle East, we compare “green” LEED buildings and conventional buildings using post-occupancy evaluation covering: (i) carefully constructed bi-lingual surveys, which address occupants’ satisfaction of all four

IEQ parameters (indoor air quality, noise, lighting, and thermal comfort) (ii) matching objective measurements for air quality and thermal comfort, including high-resolution on-site continuous monitoring of air temperature, relative humidity and CO_2 with periodic measurements of mean radiant temperature and air speed.

In addition, we assess occupant work performance through absenteeism and presenteeism rates. We show that the "green" LEED office buildings in Jordan comply with LEED specification in terms of indoor CO_2 concentration levels during the monitored period. However, this was contrary to the perception of occupants, who rated the ventilation as the IEQ aspect most in need of improvement. Indeed, the overall IAQ satisfied only 48% of the occupants in the LEED buildings, whereas it satisfied 66% of those in the conventional buildings.

In LEED buildings, the estimated percentage of monitored temperature fell within the ASHRAE 55 recommended range during working hours was between 49% – 69%, while this percentage was lower in CBs (1% - 36%). Only 73% of the TSVs were within the ASHRAE 55 acceptable range in CBs, hence failing the 80% threshold. In LEED buildings, on the other hand, 85% of TSVs were within the ASHRAE 55 acceptable comfort zone, consistent with the internationally accepted ISO 7730 PMV model, which also suggests a satisfaction rate of 85%, for the same conditions.

A surprising finding was that occupant satisfaction with IEQ aspects namely: overall IAQ, ventilation, fresh air, and sun glare is observed to be greater in the CBs, than in the "green" LEED buildings. Only noise level was perceived to be better in the LEED buildings. Two out of the four categories of IEQ, i.e. IAQ + ventilation and thermal comfort were seen to be more important issues by the occupants (accounting for 61% and 58% of the ranking scores in Table 3.8 for the CBs and the LEED buildings respectively), while the remaining two, lighting and noise, were seen as much less important (8% and 12% for CB and LEED respectively in the case of lighting, and 0% in the case of noise). While we did not objectively verify standards compliance for these aspects, it is reassuring that these aspects were broadly seen as satisfactory by the occupants, with no significant difference in satisfaction with lighting between the building types, and slightly better satisfaction in terms of noise in the LEED buildings. Absolute and relative absenteeism was slightly higher in CBs compared to LEED buildings, though with a negligible effect. No differences were reported in relative and absolute presenteeism between buildings types.

According to these results, there are a number of important changes and development, which need to be made in terms of IAQ and ventilation systems in LEED buildings in the region. A periodic assessment of LEED buildings after hand over, which covers the occupants and physical parameters of buildings should be considered to ensure that LEED buildings are not only achieving the specifications of certification but that these standards are in accordance with occupant desires. This is the first study of its kind in the Middle East, which is experiencing significant growth in both the overall number of buildings as well as green buildings. Hence further studies are merited to expand the database of building performance evaluation and help drive the better design of buildings in the region.

3.10 Acknowledgements

The authors would like to thank Mr Mualla for helping with data collection, Dr Nick McCullen for assistance with Raspberry-Pi loggers, and Dr Ian Walker for helping in the design of the questionnaire, and the management of the surveyed buildings for allowing the authors to conduct the study. This work is supported by Al-Ahliyya Amman University in Jordan. D. Fosas reports funding from the UK EPSRC project "The Active Building Centre Research Programme" [EP/V012053/1]. Electronic Supplementary Material (ESM): supplementary material is available in the online version of this article at https://doi.org/10.1007/s12273-020-0695-1.

3.11 Appendices

(a) Demographic breakdown of participants in each building classification (n.b. the number of occupants is presented with absolute values as well as relative within parentheses in the table body; relative number of occupants is broken down per category and adds to 100% within the same type of building; CB indicates conventional building).

Category	**CB ($n_{occupants}$= 241)**		**LEED ($n_{occupants}$= 261)**	
Gender				
Female	95	(39%)	128	(49%)
Male	146	(61%)	133	(51%)
Job category				
Administrative	62	(26%)	86	(33%)
Sales	37	(15%)	50	(19%)
Design	37	(15%)	39	(15%)
Executive	37	(15%)	36	(14%)

Other	68	(28%)	50	(19%)
Working experience				
0.0, 0.5)	31	(13%)	22	(8%)
[0.5, 1.0)	37	(15%)	23	(9%)
[1.0, 2.5)	54	(22%)	61	(23%)
[2.5, 5.0)	37	(15%)	65	(25%)
[5.0, ∞)	82	(34%)	90	(34%)
Daily working hours				
0, 1	-		2	(1%)
1, 3	-		6	(2%)
3, 5	4	(2%)	7	(3%)
5, 7	10	(4%)	6	(2%)
7, 8	24	(10%)	31	(12%)
8, ∞	203	(84%)	209	(80%)
Education level				
High school	15	(6%)	14	(5%)
College	23	(10%)	10	(4%)
Bachelors	158	(66%)	194	(74%)
Master	45	(19%)	43	(16%)
Number of people in the same office				
[0, 1)	106	(44%)	39	(15%)
[2, 4)	98	(41%)	35	(13%)
[4, 10)	17	(7%)	22	(8%)
[10, 24)	20	(8%)	150	(57%)
[24, ∞)	-		15	(6%)
Net monthly earning (JD)				
[0, 400)	21	(9%)	17	(7%)
[400, 700)	56	(23%)	94	(36%)
[700, 1000)	76	(32%)	61	(23%)
[1000, 1300)	16	(7%)	39	(15%)
[1300, 1600)	24	(10%)	24	(9%)
[1600, 2000)	16	(7%)	3	(1%)
[2000, ∞)	32	(13%)	23	(9%)

(b) Technical specifications of instruments used in monitoring thermal conditions and CO_2.

Measurement type	Sensor	Variable	Unit	Valid Range	Accuracy
Spot measurement	HD 32.3	T_a	°C	[0, 50]	±0.1
		RH	%	[0, 100]	±0.8
		V_a	ms^{-1}	[0.1, 5]	±0.2
Time series	Maxim IC DS18B20	Ta	°C	[-10, 85]	±0.5
(Raspberry Pi-based sensors)	AdaFruit DHT22	RH	%	[0, 100]	±2
	Sensair K30	CO_2	ppm	[0, 5000]	±30

3.12 Postscript

Our investigation in this chapter compares the design estimation and actual performance of IEQ in LEED-certified buildings. Findings show the following findings:

- LEED-certified buildings and conventional buildings comply with the standards level for indoor CO_2 concentration levels.
- The thermal environment was slightly better in LEED-certified buildings compared to the CBs.
- Occupants in CBs seem to experience higher overall satisfaction with IEQ aspects compared to those in LEED-certified buildings.
- The overall IAQ satisfied only 48% of the occupants in LEED-certified buildings, whereas it satisfied 66% of those in the CBs.
- Thermal comfort was perceived by the occupant of CBs as an issue that needed improvement.
- Occupants in LEED buildings reported ventilation as the most aspect that needs improvement.

The findings in this chapter provide empirical data to expand the international POE on green office buildings. Findings also may help building developers and decision-makers in the further development of green building design. The next chapter expands to study in-depth the occupant thermal comfort in air-conditioned buildings in several occupancy types within different countries in the ME.

4 Thermal comfort standards in the Middle East: current and future challenges

4.1 Preamble

This chapter represents the first large-scale thermal comfort field study in the ME. It reports two lines of evidence. First pooled results from a meta-analysis of existing thermal comfort studies in the ME. Second, results obtained from seven new thermal comfort field surveys conducted in 31 air-conditioned buildings over two years between 2017 and 2019 in four countries in the ME. This chapter specifically addresses RQ 3 "How suitable are international thermal comfort standards for occupants in air-conditioned buildings in the Middle East?". This chapter reports the observed and predicted thermal comfort votes of 1,101 subjects during summer and winter and illustrates the calculation of the observed and expected neutral temperature for each surveyed city. It estimates also any potential reduction in the building energy demand used for space cooling in air-conditioned buildings, if the indoor temperature is adjusted based on the occupants' preferences.

4.2 Declaration of authorship

This declaration concerns the article entitled:
Thermal comfort standards in the Middle East: current and future challenges
Publication status (tick one)
Submitted ☐ In review ☑ Accepted ☐ Published ☐
Publication details:
R. Elnaklah, A. Alnuaimi, B. Alotaibi, E. Topriska, I. Walker and S. Natarajan, Thermal comfort standards in the Middle East: current and future challenges, Building and Environment. (2021) (Under review since 1st February).
Copyright status (tick the appropriate statement):

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Candidate's contribution to the paper (%):

- Formulation of ideas: R. Elnaklah (80%) and S. Natarajan (20%).
- Design of Methodology: R. Elnaklah (80%) and S. Natarajan (20%).
- Data Collection: R. Elnaklah (46%), A, Alnuaimi (34%), B, alotaibi (5%), E, Topriska (16%).
- Data Analysis: R. Elnaklah (80%), A, Alnuaimi (5%), I, Walker (5%) and S. Natarajan (10%).
- Presentation of data in journal format: R. Elnaklah (80%) and S. Natarajan (20%).

Statement from Candidate:

This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed: Rana Elnaklah **Date** 25th Jan 2021

4.3 Abstract

Cooling energy demand has increased three-fold in the Middle East (ME) over the last 30-years. This is driven by the need to maintain thermal comfort in an extremely hot climate, and supported by rising incomes, falling costs of air-conditioning and growth in the number of buildings. The definition of thermal comfort in these buildings is drawn from "international" standards, which, though empirically derived, have no basis data from this region. Hence, we ask, to what extent do indoor conditions in the ME fall within the standards recommended range of thermal comfort, and when they do, whether they are found to be comfortable by their occupants. We present the first large-scale study of thermal comfort in the ME, consisting of two approaches: (i) a meta-analysis of data from existing studies, (ii) independent field data covering four countries representing 27% of the region's population, 31 air-conditioned buildings of different types, including "green" buildings, and 1,101 subjects. The meta-analysis demonstrates that current thermal comfort standards fail to predict thermal sensation of 94% of occupants. Our own data

show that, while indoor conditions are within standards-recommended ranges 58% of the time, only 40% of occupants find these conditions acceptable. We find evidence of overcooling in summers, with 39% occupants expressing cold discomfort. Computer models suggest that this is likely to have increased annual cooling energy demand between 13%-20%, compared to non-overcooled conditions. These results suggest the necessity of localised thermal comfort standards that mitigate excess cooling energy demand, without compromising occupant thermal comfort.

4.4 Introduction

Heating, Ventilation, and Air-Conditioning (HVAC) systems currently consume around 50% of the global building energy demand (IEA, 2013; Yang et al., 2014). In 2019, space cooling alone consumed 20% of the global electricity used in buildings (IEA, 2020). In developing countries, many of which experience warm to hot climates, population growth combined with rising incomes has resulted in increasing the energy demand for space cooling 10% between 2018 and 2019 (IEA, 2018). In low latitude countries (e.g., India, China, Africa, Northern Australia, South and Latin America, and Middle East (ME[6])), energy use for space cooling is projected to rise from its present average of 32% of total building energy consumption to 72% by 2100 (EPA, 2019), driven largely by warmer outdoor temperatures as a result of climate change.

The ME is especially vulnerable to the impact of climate change projections due to its hot arid and semi-arid environment, with extreme climate conditions (Beck et al., 2018). For example, the outdoor air temperature in summer frequently exceeds 50 °C in countries like Kuwait, Saudi Arabia, and Qatar, while in winter it drops down below 5 °C in Jordan, Syria, and Lebanon (Beck et al., 2018). Currently, the building sector in the ME consumes 28% of the total energy consumption, with 70% attributed to space cooling (IEA, 2018, 2019b; Nematollahi et al., 2016). The high space cooling demand is in response to the growing demand for better thermal comfort within the built environment, especially in non-domestic buildings (e.g., commercial, governmental, and health facilities) (Yang et al., 2014). Indeed, cooling system penetration is around 65% across the ME (IEA, 2020; KAPSARC, 2020). Today, there are 1.1 billion air-conditioning units in the ME (i.e.,

[6] There is no standard definition of the countries comprising the Middle East (ME). The most common definition classes fifteen countries namely Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestinian Territories, Qatar, Saudi Arabia, Syria, United Arab Emirates, and Yemen (Middle East Policy Council, 2020), as the ME, and is the definition used here.

three units per capita), and it is projected to increase to 3.1 billion units (five units per capita) by 2050 (Iain Campbell et al., 2018; MENAGBC, 2020; The Washington Institute for Near East Policy (WINEP), 2020). The need to drive this growth in a sustainable manner has resulted in the creation of several national-scale, and some regional-scale, voluntary Green Building Codes (GBCs). For example, the Pearl Building Rating System (PBRS) is localised to the United Arab Emirates (UAE) (Abu Dhabi Urban Planning council, 2010), whereas the Global Sustainability Assessment System (GSAS (Gulf Organization for research and developmnet (GORD), 2020)), which was originally developed within Qatar (as QSAS), has now been adopted across the region. As many of these codes are often based on international codes such as the American LEED (USGBC, 2019) or British BREEAM (BREEAM, 2019), a side effect has been the wholesale adoption of the underlying technical standards that these GBCs make reference to. In the case of thermal comfort, ASHRAE 55 (ANSI/ASHRAE 55, 2017) and ISO 7730 (ISO 7730, 2005), have been adopted as these are seen as internationally applicable. There is a well-known trajectory for such codes to transition from voluntary to mandatory status, such as through incorporation within building regulations. It is therefore not surprising that eight countries out of fifteen in the ME have now adopted ASHRAE 55 and/or ISO 7730 as part of compliance procedures within national building regulations (see Section 4.5).

However, it has often been argued that thermal comfort could be affected by the complex interplay of several factors. These are usually grouped into three categories: behavioural (e.g., individual thermal adaptation), physiological (e.g., gender, race, age), and contextual (e.g., geographic location, climate, season) – none of which are factors within the international standards (Michael A Humphreys & Nicol, 2002). While some factors have been shown to not have a major influence (e.g., gender (Vellei et al., 2017)), there is little in the literature to clearly demonstrate the effect of others, such as geography or culture (Aljawabra & Nikolopoulou, 2010; Kenawy & Elkadi, 2013). More recently, however, there is some evidence to suggest that the adoption of these standards in warm climates can produce cooler than desired indoor conditions (Alnuaimi & Natarajan, 2020).

Hence, it is important to gather evidence on whether the international thermal comfort standards, if applied, produce comfortable indoor conditions in this region. If true, a straightforward pathway for their general adoption is opened, and indeed, may support their adoption in other parts of the world. However, if the application of these standards does not consistently deliver indoor thermal comfort, then more localised standards would be needed. This is the basic question investigated in this paper. We approach this problem for the ME by constructing two independent lines of evidence. First, we conduct a meta-analysis for all existing thermal comfort studies are done in the ME to collect related evidence (section 4.7). Second, we undertake new thermal comfort field surveys in four countries within the Middle East during cooling and heating season (section 4.8). Then, we combine our independent results (section 4.9) with the meta-analysis findings to create a large-scale thermal comfort dataset, which provides the opportunity to understand the thermal comfort patterns across the ME and show the potential saving in the building energy demand for space cooling and heating (section 4.10).

4.5 Current thermal comfort standards in the ME

GBCs are usually considered more inclusive and comprehensive because they include the national building regulations as a mandatory basic level that need to be met in advance of starting the assessment process. Given the trajectory of rules transitioning from voluntary to mandatory, as stated earlier, one can expect the set of building regulations making reference to thermal comfort standards to be a subset of GBCs making reference to the same standard. Further, GBCs will also frequently lay claim to higher quality indoor environments, and hence, any evaluation of the success or failure in the provision of thermal comfort must also include an assessment of the performance of GBC-certified buildings. We therefore commence with an analysis of thermal comfort standards as adopted within GBCs in the ME.

Of the fifteen countries in the ME, eight have developed a local GBC or equivalent. Hence, these eight codes are selected to investigate which thermal comfort standards are used in the ME. These GBCs are: ARZ Building Rating System in Lebanon (Lebanon green building council, 2008), GSAS (formerly QSAS) in Qatar (Gulf Organization for research and developmnet (GORD), 2020), Green Pyramid Rating System (GPRS) in Egypt (The Egyptian Green Building Council, 2011), Israeli Green Building Standard (SI 5281) in Israel (Israel Ministry of Environmental Protection, 2016), Jordanian Green Building Guide (JGBG) in Jordan (Ministry of Public Works and Housing, 2013), Mostadam in Saudi Arabia (Sustainable Building, 2019), Palestinian Green Building Guide (PGBG) in the Palestinian Authority (Palestine Engineers Association and

Palestine Higher Green Building Council, 2013), and Pearl Building Rating System (PBRS) in UAE (Abu Dhabi Urban Planning council, 2010).

Table 4.1 Summary of thermal comfort requirements specified in the green building codes in the Middle East, • indicates that the element is explicitly mentioned in the tool and it has weight of the total scale weight; ◊ indicates that the element is implicitly mentioned in the tool, n/a indicates not available.

Tool	ARZ (Lebanon green building council, 2008)	GSAS (Gulf Organization for research and developmnet (GORD), 2020)	GPRS (The Egyptian Green Building Council, 2011)	JGBG (Ministry of Public Works and Housing, 2013)	Mostadam (Sustainable Building, 2019)	PGBG (Palestine Engineers Association and Palestine Higher Green Building Council, 2013)	PBRS (Abu Dhabi Urban Planning council, 2010)	SI 5281 (Israel Ministry of Environmental Protection, 2016)
Country	Lebanon	Qatar	Egypt	Jordan	Saudi Arabia	Palestinian Authority	UAE	Israel
Year	2008	2009	2011	2013	2019	2013	2007	2005
Thermal comfort standard	ASHRAE 55	ISO 7730 ASHRAE 55	ASHRAE 55	ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55
Assessment approach	n/a	Design stage: PMV for spaces with direct exposure to the solar heat and/or Air Diffusion Performance Index (ADPI) for other spaces Operation stage: Air temperature range of 22 – 25 °C, relative humidity range of 35% - 55%, air speed below 0.2 ms-1	n/a	n/a	-0.5≤ PMV ≤ 0.5 PPD ≤ 10% -0.7 ≤ PMV ≤ 0.7 PPD ≤ 15%	Class I: -0.5≤ PMV ≤ 0.5 PPD ≤ 10% Class II: -0.7 ≤ PMV ≤ 0.7 PPD ≤15%	Mechanical class I: -0.5≤ PMV ≤ 0.5 PPD ≤ 10% Mechanical class II: -0.7 ≤ PMV ≤ 0.7 PPD ≤ 15% Mixed-Mode ventilation (class B and C): 90% acceptability limits	-0.5≤ PMV ≤ 0.5 PPD ≤ 10%
Thermal Comfort Requirement								
Thermal zoning							•	
Occupant control		◊			•	•	•	
Occupancy sensor linked to HVAC					•	•		
Operable windows		•				•	•	•
Thermal comfort modelling					•		◊	
Post-occupancy thermal comfort survey		•						

shows that each of the investigated codes adopts either or both the ISO7730 and ASHRAE 55 standards. This is not surprising since they are based either on LEED and/or

BREEAM, which use these standards. The thermal comfort standards and requirements are included in these codes either under the Indoor Environment Quality (IEQ) aspect (as in ARZ, GSAS, GPRS, PGBG, and JGBG) or under other aspects, i.e., health and wellbeing, liveable buildings, health, and comfort.

There are minor differences in the implementation of the international standards within each of the eight codes, observable through the difference in treatment of the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfaction (PPD) indices, that specify the acceptable range of thermal conditions for building users. Whereas PBRS and PGBG explicitly state the use of two classes of PMV/PPD for mechanically ventilated and mixed-mode buildings, broadly corresponding to the classes contained in ISO7730; SI 5281 and Mostadam only use the range for "normal" expectation, i.e., PMV [-0.5, +0.5] and PPD <10%. GSAS is unique within this group to separate design and operation stages, the latter being required to adhere to thermal conditions that would apply for "normal" levels of thermal expectation (i.e., the same as SI 5281 and Mostadam) but being pre-calculated assuming western office attire and standard levels of metabolic activity rates. This is odd, given that these conditions would be an automatic requirement within ISO 7730 for such levels of activity and attire, but precludes adjustment for other conditions. Closer inspection of the thermal comfort requirements in

Table 4.1 Summary of thermal comfort requirements specified in the green building codes in the Middle East, • indicates that the element is explicitly mentioned in the tool and it has weight of the total scale weight; ◊ indicates that the element is implicitly mentioned in the tool, n/a indicates not available.

Tool	ARZ (Lebanon green building council, 2008)	GSAS (Gulf Organization for research and developmnet (GORD), 2020)	GPRS (The Egyptian Green Building Council, 2011)	JGBG (Ministry of Public Works and Housing, 2013)	Mostadam (Sustainable Building, 2019)	PGBG (Palestine Engineers Association and Palestine Higher Green Building Council, 2013)	PBRS (Abu Dhabi Urban Planning council, 2010)	SI 5281 (Israel Ministry of Environmental Protection, 2016)
Country	Lebanon	Qatar	Egypt	Jordan	Saudi Arabia	Palestinian Authority	UAE	Israel
Year	2008	2009	2011	2013	2019	2013	2007	2005
Thermal comfort standard	ASHRAE 55	ISO 7730 ASHRAE 55	ASHRAE 55	ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55

Assessment approach	n/a	Design stage: PMV for spaces with direct exposure to the solar heat and/or Air Diffusion Performance Index (ADPI) for other spaces Operation stage: Air temperature range of 22 – 25 °C, relative humidity range of 35% - 55%, air speed below 0.2 ms-1	n/a	n/a	-0.5≤ PMV ≤ 0.5 PPD ≤ 10% -0.7 ≤ PMV ≤ 0.7 PPD ≤ 15%	Class I: -0.5≤ PMV ≤ 0.5 PPD ≤ 10% Class II: -0.7 ≤ PMV ≤ 0.7 PPD ≤15%	Mechanical class I: -0.5≤ PMV ≤ 0.5 PPD ≤ 10% Mechanical class II: -0.7 ≤ PMV ≤ 0.7 PPD ≤ 15% Mixed-Mode ventilation (class B and C): 90% acceptability limits	-0.5≤ PMV ≤ 0.5 PPD ≤ 10%
Thermal Comfort Requirement								
Thermal zoning							•	
Occupant control		◊			•	•	•	
Occupancy sensor linked to HVAC					•	•		
Operable windows		•				•	•	•
Thermal comfort modelling					•		◊	
Post-occupancy thermal comfort survey		•						

shows that among GSAS, PGBG, PBRS, Mostadam, and SI 5281, the thermal comfort credits are clustered around occupant control over indoor temperature, thermal zoning, the requirement for operable windows, and occupancy sensors. Thermal comfort modelling at the design stage is required explicitly in Mostadam, while it is implicitly mentioned in PBRS and not included within the total assigning credits. Only GSAS requires a thermal comfort survey after occupancy as a mandatory credit. The lack of any of the above details in ARZ, GPRS, and JGBG, is striking in comparison.

Overall, therefore, we find that there is a clear trend for GBCs in the region to adopt international thermal comfort standards. Although they prescribe some minor adjustments, one cannot conclude that this results in localisation since there is neither underpinning localised evidentiary basis for their use nor an implicit adjustment to the standards based on expert knowledge or experience. From this, we can inductively reason that buildings in the ME, in general, are likely to conform to an international thermal comfort standard when designed to be standards compliant.

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Table 4.1 Summary of thermal comfort requirements specified in the green building codes in the Middle East, • indicates that the element is explicitly mentioned in the tool and it has weight of the total scale weight; ◊ indicates that the element is implicitly mentioned in the tool, n/a indicates not available.

Tool	ARZ (Lebanon green building council, 2008)	GSAS (Gulf Organization for research and developmnet (GORD), 2020)	GPRS (The Egyptian Green Building Council, 2011)	JGBG (Ministry of Public Works and Housing, 2013)	Mostadam (Sustainable Building, 2019)	PGBG (Palestine Engineers Association and Palestine Higher Green Building Council, 2013)	PBRS (Abu Dhabi Urban Planning council, 2010)	SI 5281 (Israel Ministry of Environmental Protection, 2016)
Country	Lebanon	Qatar	Egypt	Jordan	Saudi Arabia	Palestinian Authority	UAE	Israel
Year	2008	2009	2011	2013	2019	2013	2007	2005
Thermal comfort standard	ASHRAE 55	ISO 7730 ASHRAE 55	ASHRAE 55	ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55	ISO 7730 ASHRAE 55
Assessment approach	n/a	Design stage: PMV for spaces with direct exposure to the solar heat and/or Air Diffusion Performance Index (ADPI) for other spaces Operation stage: Air temperature range of 22 – 25 °C, relative	n/a	n/a	$-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$ $-0.7 \leq$ PMV ≤ 0.7 PPD $\leq 15\%$	Class I: $-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$ Class II: $-0.7 \leq$ PMV ≤ 0.7 PPD $\leq 15\%$	Mechanical class I: $-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$ Mechanical class II: $-0.7 \leq$ PMV ≤ 0.7 PPD $\leq 15\%$ Mixed-Mode ventilation (class B and C): 90% acceptability limits	$-0.5 \leq$ PMV ≤ 0.5 PPD $\leq 10\%$

	humidity range of 35% - 55%, air speed below 0.2 ms-1				
Thermal Comfort Requirement					
Thermal zoning				•	
Occupant control	◊	•	•	•	
Occupancy sensor linked to HVAC		•	•		
Operable windows	•		•	•	•
Thermal comfort modelling		•		◊	
Post-occupancy thermal comfort survey	•				

4.6 Research objectives

This study is designed to examine whether air-conditioned buildings in the ME fall within the recommended ranges of thermal comfort identified by the applied standards in this region, and when they do, to what extent they are found to be comfortable by their occupants. To address this, we start by a meta-analysis approach to aggregate the outcomes of multiple thermal comfort studies in the ME (Section 4.7) and then, we conduct new field surveys in four countries: Jordan, Qatar, Saudi Arabia, and the United Arab Emirates, representing 27% of the ME population, using the definition suggested earlier (Section 4.4). Our detailed objectives are:

- To perform a meta-analysis of previous thermal comfort research in air-conditioned buildings in the ME.
- To assess thermal conditions in GBC-certified and typical air-conditioned buildings in the ME against both the applied international thermal comfort standards and those proposed by localised GBCs.
- To compare the predicted mean vote (PMV) and observed thermal sensation vote (TSV) in all building types and investigate any seasonal differences.
- To calculate the difference between predicted and observed neutral (comfort) temperatures and estimate any potential reduction in the building energy use for space cooling and heating based on the obtained differences, if any.

4.7 Meta-analysis of evidence in the ME

There are two methods to perform the meta-analyses, either using individual participant data (i.e., raw data collected by multiple studies) or aggregate data (i.e., available evidence from literature) (Burke et al., 2017). We rely on the latter approach, as the raw data were not publicly available. First, we systematically review the relevant literature (DeLuca et al., 2008), including the recently released ASHRAE Global Thermal Comfort Database II (Földváry Ličina et al., 2018). We determine the eligibility of studies for our meta-analysis based on two criteria: (i) the operation mode in the surveyed buildings (i.e., air-conditioned only), and (ii) the available thermal comfort data (Figure 4.1). Second, we extract the aggregate data from selected studies and compute summary statistics from each study (Debray et al., 2013).

Table 4.2 summarises the eight included studies in the meta-analysis. All studies investigated occupant thermal comfort in air-conditioned buildings in the ME and were done in the past ten years (2010 - 2020) during the cooling season. In the ME, the cooling season varies according to the climate zone, for example, coastal cities, such as Jeddah, Doha and Bahrain are humid and very hot throughout the year, thus air-conditioning is used for space cooling continuously. Whereas in cities at high elevations such as Amman, Beirut, and Damascus, the use of air conditioning for space cooling is limited to four months only between June and September; while in December, January and February, there is some space heating demand usually delivered via the air conditioning system or through supplementary heating. In these latter cities, therefore, there exists potential for natural ventilation during the remaining five months (i.e., March, April, May, October, and November).

Among the analysed studies, offices comprise the most studied group of buildings (80% of the total sample size (Indraganti & Boussaa, 2017, 2018), some studies include homes (Al-ajmi & Loveday, 2010a; Alshaikh et al., 2014), mosques (Al-ajmi, 2010a; Kotbi et al., 2012), hospitals (covering patients only) (Alotaibi et al., 2019), and educational buildings, i.e. university campuses (Al-ajmi, 2020). The studies cover three countries namely Kuwait, Qatar, and Saudi Arabia and employ transverse sampling, except one which has a longitudinal design (Indraganti & Boussaa, 2017).

When all data are pooled, the resulting dataset covers 76 air-conditioned buildings and 2,825 subjects in the age range $\in$ [21, 34] years (mean = 31 years, s = 4.6 years), hence, this is a young sample. All studies (except one (Alshaikh et al., 2014), report aggregate data for five standard thermal comfort parameters: air temperature (T_a), relative humidity (RH), air speed (V_a), metabolic rate (met), and clothing thermal insulation (clo). Three studies report either the mean radiant temperature (T_r) (Alotaibi et al., 2019; Indraganti & Boussaa, 2017) or the globe temperature (T_g), from which T_r can be derived (Indraganti & Boussaa, 2017, 2018). All studies report the operative temperature (T_o), except two studies (Al-ajmi, 2010a; Al-ajmi & Loveday, 2010a). The summary statistics for these studies shown in Table 4.2 are based on a total of 7,077 records of environmental and subjective observations. We observe that mean clothing thermal insulation was 0.94 clo (s = 0.26 clo), with the lowest mean of 0.42 clo in homes. Estimated metabolic rates varied considerably between 2.3 met for employees in office buildings to 0.67 met in homes (dataset mean 1.24 met, s = 0.48 met).

RH ranged between 35% and 60% (mean 44%, s = 8.6%) with Kuwait at the lower end and Saudi Arabia at the higher end of the scale. V_a does not exceed 0.25 ms^{-1} (mean = 0.11 ms^{-1}, s = 0.09 ms^{-1}) in all studies. Means for T_a (23.2°C, s = 1.56 °C), T_r (23.1 °C, s = 0.63 °C), T_g (23.3 °C, s = 0.49 °C) and T_o (23.1 °C, s = 0.86 °C) were comparable through the dataset. Mean T_a ranged between 22– 24 °C, with the exception of data from homes in Saudi Arabia which reported a mean T_a of 27 °C.

An average of 43% of votes in the dataset can be classified as neutral (i.e., TSV $\in$ [-1, +1], Figure 4.2.a). Hence, none of these buildings achieve 80% acceptability as recommended by the ASHRAE 55 standard. A significant proportion of the votes (26% on average) demonstrate cold discomfort (i.e., TSV < -1), which is substantially higher than the average vote for warm discomfort (21%).

TSV is cooler on average than predicted by PMV in all types of buildings except in the hospital study (Figure 4.2.b and c). Hence, the observed neutral temperatures based on TSV ($T_{n(TSV)}$), in these buildings were higher compared to those predicted by PMV ($T_{n(PMV)}$), which underestimated neutrality by an average of 2.1 K (Figure 4.2.d). A possible cause for the hospital study resulting in PMV underestimating TSV, is that this study looks at thermal comfort in patients suffering from cardiovascular and respiratory diseases and are hence not directly comparable to healthy subjects in other studies. Here, we find that mean PMV = -0.5 compared to mean observed TSV = +0.3, corresponding to $T_{n(TSV)}$ = 22.7 °C and $T_{n(PMV)}$ = 25.6 °C, i.e. a difference of 2.9 K. While the authors of that study speculate that lowered met and clo may be the cause for this unusual result, this would seem counterintuitive and can hence be considered as not fully understood.

Overall, the meta-analysis suggests, with the exception of the hospital, as above, that the PMV model usually results in cooler conditions than those preferred by building occupants in the ME. However, given that the data cover only three countries and only typical buildings, there is clear potential for additional data from other locations including from more modern "green" buildings. That all the extant studies are from the cooling season (i.e., summer and autumn) also suggests the need to investigate the heating season, where appropriate. Finally, it would be useful to understand to what extent the results of the hospital study are due to the survey being confined to patients and not staff. Hence, the next part of this paper aims to increase the coverage of locations, seasons, building types and occupant types for thermal comfort data in the ME.

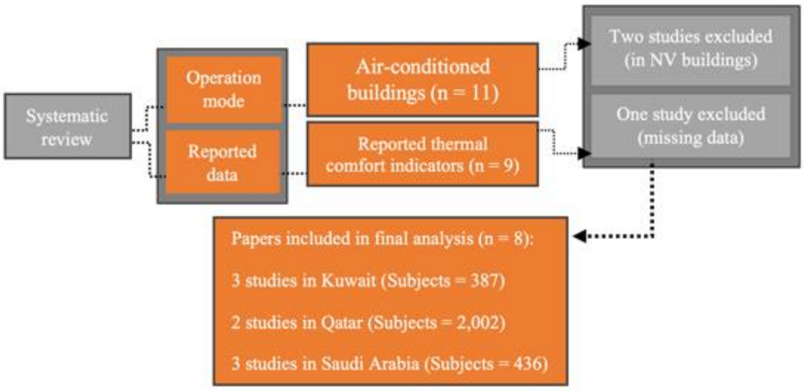

Figure 4.1 Schematic flow diagram of literature screening process, including the number of potentially relevant studies and the final number of included studies that met the two inclusion criteria.

Table 4.2 Descriptive summary statestic of the existing field thermal comfort studies in air-conditiond buildings in the ME during cooling season, the reported values for thermal comfort parameters in this table represent the mean for each study. Note: the mean value of age is not reported in two studies, as instead they report the percentage of multiple age group, ($n\_buildings = 76; n\_Subjects = 2{,}825$).

						Reported mean within each study													
Ref	Location	Bldg. Type	Bldg (n)	Subject (n)	Vote (n)	Age (y)	clo	met	T_a (°C)	T_g (°C)	T_r (°C)	V_a (ms-1)	RH (%)	T_o (°C)	PMV	TSV	$T_{n(PMV)}$ (°C)	$T_{n(TSV)}$ (°C)	Diff (°C)
(Al-ajmi & Loveday, 2010b)	Kuwait	Homes	25	111	111	32.1	0.90	1.20	22.7	-	-	0.13	34.5	23.7	0.13	-0.28	23.3	25.2	1.90
(Al-ajmi, 2010b)	Kuwait	Mosques	6	140	140	32.6	0.93	1.30	23.0	-	-	0.23	44.1	23.9	0.19	-0.26	23.3	26.1	2.80
(Kotbi et al., 2012)	Saudi Arabia	Mosques	1	281	422	-	1.13	1.30	21.7	-	-	0.25	31.9	21.5	0.01	-0.19	21.5	22.3	0.80
(Alotaibi et al., 2019)	Saudi Arabia	Hospital	1	120	120	-	1.30	0.80	23.1	-	23.4	0.04	48.3	23.3	-0.5	0.32	25.6	22.7	-2.90
(Indraganti & Boussaa, 2017)	Qatar	Offices	9	828	1,926	32.7	1.00	1.10	23.1	22.7	22.5	0.02	44.9	22.8	0.04	-0.23	23.7	24.1	0.40
(Indraganti & Boussaa, 2018)	Qatar	Offices	10	1,174	3,742	32.9	0.80	2.30	23.8	23.4	-	0.04	45.7	-	-	-0.54	-	24.8	-
(Al-ajmi, 2020)	Kuwait	Campuses	7	136	136	21.6	1.01	1.30	22.8	-	-	0.09	46.0	23.3	0.50	0.11	18.9	22.9	4.0
(Alshaikh et al., 2014)	Saudi Arabia	Homes	17	35	480	34.0	0.42	0.67	27.0	-	-	-	60.0	-	-	1.30	-	-	-
Mean (SD)						31 (4.6)	0.94 (0.3)	1.2 (0.4)	23.2 (1.5)	23.3 (0.4)	23.1 (0.6)	0.11 (0.1)	44.2 (8.6)	23.1 (0.8)	0.06 (0.3)	0.03 (0.6)	23.3 (2.3)	24.3 (1.4)	

Total	76	2,825	7,077

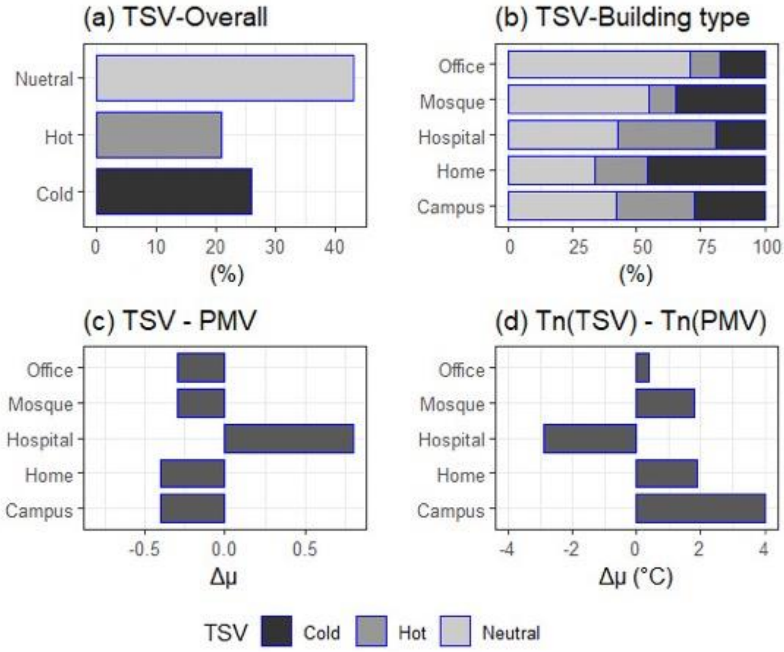

Figure 4.2 Summary results of the meta-analysis with $n_{buildings} = 76; n_{occupants} = 2{,}825$, (a) raw TSV distribution for the dataset, (b) TSV distributions split by building type, (c) the difference between mean scores (i.e., Δμ = TSV-PMV) based on the building type, i.e. (Δμ > 0) indicates TSV is greater than PMV, (d) the difference between mean neutral temperatures derived from TSV ($T_{n(TSV)}$) and PMV ($T_{n(PMV)}$).

4.8 New thermal comfort dataset in the ME: methods

To achieve the aim outlined at the end of Section 4.7, we undertook seven standardised thermal comfort field surveys over three years between May 2017 and Sept 2019 (Figure 4.3), using methods described in the following sections.

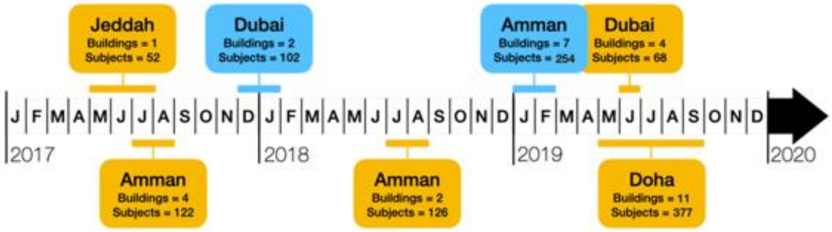

Figure 4.3 Timeline of data collection in the present study. Data were collected between May 2017 and Sept 2019 in four countries in the ME, Yellow represents studies undertaken in the summer, and blue, winter. The length of bars adjacent to each label indicates the months over which data were collected. $n\_buildings = 31; n\_subjects = 1{,}101$.

4.8.1 Outdoor conditions in the survey areas

According to the widely used Köppen climate classification (Beck et al., 2018), the climate for Doha, Dubai and Jeddah are classified as hot desert (BWh), with extremely hot summers and warm dry winters. Amman, on the other hand, is classified as a composite climate, i.e., one with hot semi-arid conditions (BSh) but bordering on cold semi-arid (BSk), with a long hot summer and short cold winter (DOS, 2016). However, this is a broad classification, and we hence use the annual heating degree days (HDDs) and cooling degree days (CDDs) for each city to illustrate how winters and summers are distributed (Table 4.3). We find that, while Doha and Jeddah do not experience wintry conditions (4 and 0 HDDs respectively), there may be some merit in investigating winter comfort in Dubai (21 HDDs) and definitely for Amman (873 HDDs). CDDs, on the other hand, are uniformly large. Thus, our field surveys were conducted in peak summer for all cities and peak winter in Amman and Dubai only.

Table 4.3 also presents the mean daily outdoor air temperature (T_{out}) and relative humidity (RH_{out}) in the surveyed cities during the time of the surveys, using data obtained from local weather stations. It is noteworthy that observed temperatures during the studies in Amman and Doha are likely to be higher than shown due to the well-known urban heat island effect, given that the data were obtained from the nearby airport (Gedzelman et al., 2003).

Outdoor summer mean temperatures are comparable in Amman, Dubai, and Jeddah with a range of 32.6 °C and 34.1 °C, while Doha had higher mean T_{out} of 40.5 °C. In Amman, where we have data from two consecutive summers, mean T_{out} in summer 2017 was slightly lower compared to the same time period in the following year 2018, with a difference of 1.1 °C. In winter, the mean T_{out} in Amman (10.4 °C) was lower than in Dubai (20.1 °C). The relative humidity ranges in Amman and Dubai during winter were higher than in summer. The RH_{out} range in Jeddah varied between 31.9% - 91% and was comparatively higher than the RH_{out} in Doha.

Table 4.3 The daily mean outdoor temperature (T_{out}) and relative humidity (RH_{out}) recorded during the study periods in Amman, Doha, Jeddah and Dubai. Annual heating degree days (HDD) and annual cooling degree days (CDD) are calculated using a base temperature [> 18 °C and < 18 °C], respectively.

City	Amman[1]			Doha[2]	Jeddah[3]	Dubai[4]	
Climate	BSh + BSK			BWh	BWh	BWh	
HDDs	873			4	0	21	
CDDs	3,814			5,006	6,587	5,392	
Time of survey	Jul – Aug 2017	Jul – Aug 2018	Jan – Feb 2019	May 2019	May – Jul 2017	Dec – Jan 2017 - 18	Jun 2019
T_{out} (°C)							
Mean	33.2	34.1	10.4	40.5	32.6	20.1	33.4
Max.	40.1	41.2	22.0	45.5	42.6	31.3	36.7
Min.	25.3	26.1	5.0	38.0	23.8	12.9	25.3
Range	[25.3, 40.1]	[26.1, 41.2]	[5.0, 22.0]	[38.0, 45.5]	[23.8, 42.6]	[12.9, 31.3]	[25.3, 36.7]
RH_{out} (%)							
Mean	42.3	47.4	70.3	46.6	49.9	66.4	62.3
Max.	52.1	56.6	75.1	58.0	91.0	80.1	78.7
Min.	13.4	15.1	69.1	37.0	31.9	50.5	41.1
Range	[13.4, 52.1]	[15.1, 56.6]	[69.1, 70.3]	[37, 58]	[31.9, 91.0]	[50.5, 80.1]	[41.1, 78.7]

Data sources:
[1]Jordan meteorological department, Amman civil Airport
[2]Department of meteorology, Civil Aviation Authority, Doha
[3]Department of meteorology, King Abdul-Aziz University, Jeddah
[4]National center of meteorology, UAE

4.8.2 Sampling

In the literature, there are two common methods for undertaking thermal comfort surveys: (i) longitudinal with repeated measures, usually with a small sample size (M. A. Humphreys et al., 2013) and (ii) transverse with a large number of responses collected once (Feriadi & Wong, 2004). Our interest is in investigating indoor conditions and comfort across a large number of buildings and hence the latter method is used. Surveys were conducted in the four locations discussed earlier and thermal comfort data were collected using a standardised questionnaire ((ANSI/ASHRAE 55, 2017), Appendix (a)), as well as the necessary objective data (see Section 4.8.3). Data were obtained from 1,101 subjects from 31 different buildings, with each subject providing one response. A range of non-domestic occupancy types were covered, including twenty-five office buildings (n = 849), three schools (n = 98), two mosques (n = 102), and one hospital (nursing staff only, n = 52).

Surveyed buildings were constructed in the last twenty years, twenty-six buildings are mechanically air-conditioned, and five buildings have mixed-mode ventilation (Figure 4.4). Seven of the office buildings are green-certified, under either local GBCs (e.g., JGBG, GSAS) or the international LEED. In addition, the surveyed buildings in Dubai and Jeddah were recipients of regional design awards and can therefore be considered as high-quality (see Appendix (b)) for the specific details of the investigated buildings). All subjects have voluntarily participated in the survey, prior informed consent being obtained. A comprehensive profile of the participating subjects is presented in Table 4.4.

Figure 4.4 Examples of the surveyed buildings in this study, (a) mosque in Dubai, (b – e) office buildings in Amman, (f) hospital in Jeddah (source: IMC Research Centre, Saudi Arabia, reproduced with permission), (g) example of mixed-mode ventilation office in Amman, (h) example of fully HVAC office, and (i) interior shot of prayer hall in the mosque, $n_{buildings} = 31$.

Table 4.4 Comprehensive profile of subjects in each surveyed city. Height, age, and weight data for Dubai are unavailable, $n\_subjects = 1{,}101$.

City	Sample (n)	Gender		Height (cm)		Weight (Kg)		Age (y)	
		Female	Male	Mean	SD	Mean	SD	Mean	SD
Amman	502	223	279	172.2	11.2	76.8	13.3	29.3	5.3
Doha	377	70	307	169.6	10.9	77.6	16.3	38.2	9.3
Dubai	170	23	79	-	-	-	-	-	-
Jeddah	52	39	14	160.9	7.6	65.2	12.2	34.6	7.2

4.8.3 Thermal comfort parameters measurements

We measure all four physical parameters affecting thermal sensation (i.e., T_a, T_r, RH, and V_a) in all surveyed buildings, except for the two buildings in Dubai during summer, where only measurements for T_a and RH were possible. Thus, data from Dubai (summer) survey are used to gain an idea of the indoor thermal conditions, while the PMV calculation for these two buildings was not possible, due to the absence of other thermal comfort indices. The measurements of the four physical parameters in all buildings were coincident with the time of each individual survey. In Amman, Doha, and Jeddah two instruments were used to monitor all parameters, SWEMA (SWEMA, 2020) and HD 32.3 (Delta OHM, 2019), both compliant with ISO 7726 (EN ISO 7726, 2001) and ISO 7730 (ISO 7730, 2005) standards. In Dubai (winter) study, an Extech HT200 heat stress wet bulb globe thermometer was used to monitor T_a, T_r, and RH, and ATP unidirectional hot wire thermo-anemometer was used to simultaneously measure V_a. The latter set while not being ISO compliant, produces data of sufficient accuracy for use in fieldwork (e.g., (Maykot et al., 2018)). Technical specifications of all instruments are in Appendix (c) .

The sample period of T_a, T_r, RH, and V_a was five minutes including two minutes for sensors to stabilise and additional three minutes to provide a stable PMV reading. Measurements in the office buildings, schools (staff room), and hospital (nursing stations and corridors) were taken at height 60 – 110 cm from the ground level, and the instrument was located on the subject's desk (Figure 4.5. a and b) (Richard J. de Dear & Gail Schiller Brager, 1998), during working hours between 09:00 – 17:00. In the mosques, measurements were taken at height 60 cm above the floor level for seated subjects as specified in ISO 7726 and ASHRAE 55, the instruments were located in the main prayer hall during Friday's congregational prayer, i.e., at maximum occupancy. The clothing thermal insulation level was calculated based on ASHRAE 55 and ISO 9920 (EN ISO 9920, 2009) (Figure 4.5. c - e). Similarly, the metabolic rate of subjects was calculated based on the standard tables provided by ASHRAE 55 and ISO 8996 (EN ISO 8996, 2004).

Figure 4.5 The instrument setup in surveyed buildings (a and b), examples of indoor subjects' summer clothing (c), winter clothing (d), and female subject with headwear (e).

4.8.4 Subjective measurements

The questionnaire consists of two sections. The first pertains to socio-demographic data on age, gender, height, weight, job role, and nationality. The second section covers the standardised thermal comfort survey based on ASHRAE 55. The survey was designed and written in English and translated to Arabic as most respondents speak Arabic as a first language. In Doha, Dubai and Jeddah, classical Arabic was used as it is the common dialect, however, for respondents in Amman, the Levantine-Arabic dialect was used (see Appendix (a)). This resulted in subtle but important differences in the coding of the questionnaire, particularly for TSV (Albadra et al., 2017). The Arabic and English versions were combined with a consent form and distributed randomly within the surveyed buildings. The questionnaire was paper based instead of online to promote the response rate, as some subjects, i.e., those at prayer and nurses did not have access to a computer or internet connection during the survey time. The survey completion time ranged between 40 - 60 seconds, with ten multiple-choice questions, all completed concurrently with the sensor measurement, per Section 4.8.3. All the buildings' managers/owners were interviewed to introduce the research idea and their written consent was obtained. While extraneous factors such as family circumstances, driving to work etc. may affect perceptions, these are not explicitly explored here due to the need to keep survey times low and thus maximise response rates, whilst being consistent with other studies. This is somewhat mitigated by the cross-sectional nature of the survey that will reduce the effect of aleatory uncertainties, though not systematic bias.

4.8.5 Analysis methods

A total of 1,101 data points was aggregated, analysed, and presented based on three levels namely location, building type, and season. Operative temperatures (T_o) were calculated per ISO 7726 (EN ISO 7726, 2001). As our data are numerical, differences in means are analysed using standard statistical inference, i.e., *t*-test, 95% confidence intervals and Cohen's well-known d metric for effect size. The mixed-effects model was used to test the differences between data and deal with non-independence. PMV was classified into three categories: cold discomfort $\in$ [-3, -0.5), neutral $\in$ [-0.5, +0.5] and hot discomfort $\in$ (+0.5, +3], since PMV ±0.5 is considered neutral for typical buildings, Category II in ASHRAE 55 (ANSI/ASHRAE 55, 2017). Although hospitals and schools could be classified as Category I buildings, where PMV ±0.2 would be considered neutral, we do not use this definition for consistency with the other data; and the fact that we are surveying only staff in the hospitals and schools.

Observed TSV were classified into cold $\in$ [-3, -1), neutral or comfort $\in$ [-1, +1] and hot $\in$ (+1, +3]. This choice of neutrality is consistent with other studies in the literature (Indraganti & Boussaa, 2018) and relates to the likelihood of the TSV scale being interpreted as ordinal, rather than interval, during subject self-completion. Note that this is likely to suggest a wider neutral band in the observed TSV than would be the case with a band consistent with PMV, and hence lead to an *underestimate* of the cold and hot discomfort classification on either side of neutral.

4.8.5.1 Calculating neutral (comfort) temperature

Simple linear regression is used to calculate the neutral temperature (T_n) from PMV and TSV for each surveyed city. We plot observed TSV and PMV against T_o and identify the neutral temperature as the temperature when the mean of PMV or TSV equals zero. We thus use the following equations:

$$\mathrm{TSV} = \alpha \mathrm{T_o} + b \tag{7}$$

$$\mathrm{PMV} = \alpha \mathrm{T_o} + b \tag{8}$$

$$\mathrm{T_n} = -b/\alpha \tag{9}$$

where (α) indicates the regression coefficient (gradient), and (b) refers to the intercept on the y-axis, i.e., TSV or PMV. For data with a small disparity in operative temperatures (e.g., Amman), we instead use the well-known Griffith's method to compute the neutral temperature derived from TSV using following equation:

$$\mathrm{T_n} = \mathrm{T_o} + (0 - \mathrm{TSV})\ /G \tag{10}$$

where G indicates the Griffith's constant. There are several commonly used values for G in the literature ranging ∈ [0.25/K, 0.5/K]. We use G = 0.5/K in line with similar studies in the ME, such as (Indraganti & Boussaa, 2018; Zaki et al., 2017). $\mathrm{T_n}$ is difficult to calculate with a small dataset (M. Humphreys et al., 2015), and hence was not computed for schools and mosques in Doha and Dubai respectively. All analysis is conducted using R (R Core Team, 2019), due to the convenient availability of the 'comf' package (Schweiker et al., 2019) for thermal comfort plus data management and plotting packages such as the 'tidyverse' family (Wickham et al., 2019) and 'cowplot' (Claus O. Wilke, 2020).

4.8.5.2 Simulation of building energy consumption

We carried out energy model simulations for the calculated $\mathrm{T_{n(PMV)}}$ and observed $\mathrm{T_{n(TSV)}}$ to illustrate the variation in building energy demand for the two indices. The well-known EnergyPlus building energy simulator (EnergyPlus, 2019), is used with ANSI (American National Standards Institute)/ASHRAE/IES (Illuminating Engineering Society) Standard 90.1 prototype building models for our analysis (Deru et al., 2011).

The simulation is done for two occupancy types: office buildings in Amman and Doha (medium office prototype building) and hospital in Jeddah (hospital prototype building) (see Appendix (d)). The schools and mosques were excluded due to small sample sizes and hence no predicted T_n, as mentioned earlier. The selected models resemble the real size and function of the buildings where the data were originally collected to maintain suitability with the building energy simulation results. Considering the default commercial prototype building model operational mode for both cooling and heating and the calculated $T_{n(PMV)}$ and $T_{n(TSV)}$, the cooling and heating setpoints for occupancy hours were adjusted to reflect the recommended upper and lower neutral temperature conditions. Amman, Doha and Jeddah models are simulated with the three calculated neutral temperatures using TSV and PMV as building setpoint temperatures in each city's climate respectively.

4.9 Results

This section presents results of the data obtained from our field study covering 31 air-conditioned buildings, four occupancy types, and 1,101 subjects, during summer and winter.

4.9.1 TSV and ASHRAE 55 comfort zones

Table 4.5 illustrates the mean scores of measured thermal comfort parameters based on season, city and building type. The mean T_a over summer and winter is within a relatively narrow range [21.7 °C, 24.0 °C], or 2.3 K, for all the buildings. RH was slightly higher in summer (pooled mean 46%) than in winter (pooled mean 43%) but over a wide range [36%, 58%]. V_a ranged between [0.05 ms^{-1}, 0.17 ms^{-1}] which is below the maximum acceptable air speed of 0.20 ms^{-1} given in the ASHRAE 55 standard.

For the subjects in the survey, the mean values of metabolic rate ranged between 1.08 met for sitting with passive work in office buildings and 2.49 met for praying in the mosques. In all surveyed cities, most (92%) male subjects were wearing western clothing, with the remaining wearing non-western clothing with clo value varied between 1.10 - 1.57 clo. A small proportion (22%) of female respondents wore headwear (Figure 4.5. e), which resulted in an increased insulation value of 0.03 clo (Havenith et al., 2015), with the rest wearing western clothing, with no headwear at 1.08 clo. Surprisingly, the clo value of subjects in summer was higher than in winter, with difference +0.03 clo in Amman, and +0.20 clo in Dubai. The lowest clo value was observed in the hospital in Jeddah, as nursing staff wear very light uniform (mean = 0.59 clo).

Figure 4.6 compares the observed thermal comfort zones in all surveyed buildings among the four cities to the recommended comfort zone by ASHRAE 55 standard (ANSI/ASHRAE 55, 2017). We observe that all surveyed buildings in Amman and Doha were within the recommended comfort zone during summer and winter, whereas the thermal comfort zone in mosques in Dubai was shifted to the left side and this refers to the high metabolic rate in mosques (mean = 2.5). The hospital in Jeddah was also completely outside the standard-recommended comfort zone. Hence, we can conclude that the buildings in Amman and Doha were thermal comfort standards compliant whereas those in Dubai and Jeddah were not.

Table 4.5 Summary of the monitored thermal comfort parameters in the surveyed buildings in the four cities during summer and winter, Ta and Va were not available for Dubai (summer) survey, $n\_buildings = 31, n\_subjects = 1{,}101$.

Season	City	Bldg. Type	clo		met		T_a (°C)		T_r (°C)		RH (%)		V_a (ms^{-1})	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Summer	Amman	Office	1.3	0.05	1.2	0.18	21.7	1.76	22.0	1.82	37.4	3.29	0.1	0.15
	Doha	Office	1.1	0.26	1.2	0.00	23.8	1.39	23.8	1.44	47.8	8.86	0.2	0.19
	Doha	School	1.1	0.19	1.2	0.00	23.7	0.96	23.9	1.28	42.2	3.53	0.2	0.18
	Dubai	School	1.2	0.12	1.2	0.10	24.0	1.23	-	-	57.7	3.59	-	-
	Jeddah	Hospital	0.6	0.05	1.1	0.12	21.8	1.36	22.1	1.32	45.1	2.11	0.1	0.11
Winter	Amman	Office	1.3	0.13	1.2	0.20	22.1	0.84	22.1	0.87	35.6	2.74	0.2	0.09
	Dubai	Mosque	1.0	0.31	2.5	0.23	23.3	1.73	23.2	1.62	51.2	4.00	0.1	0.07

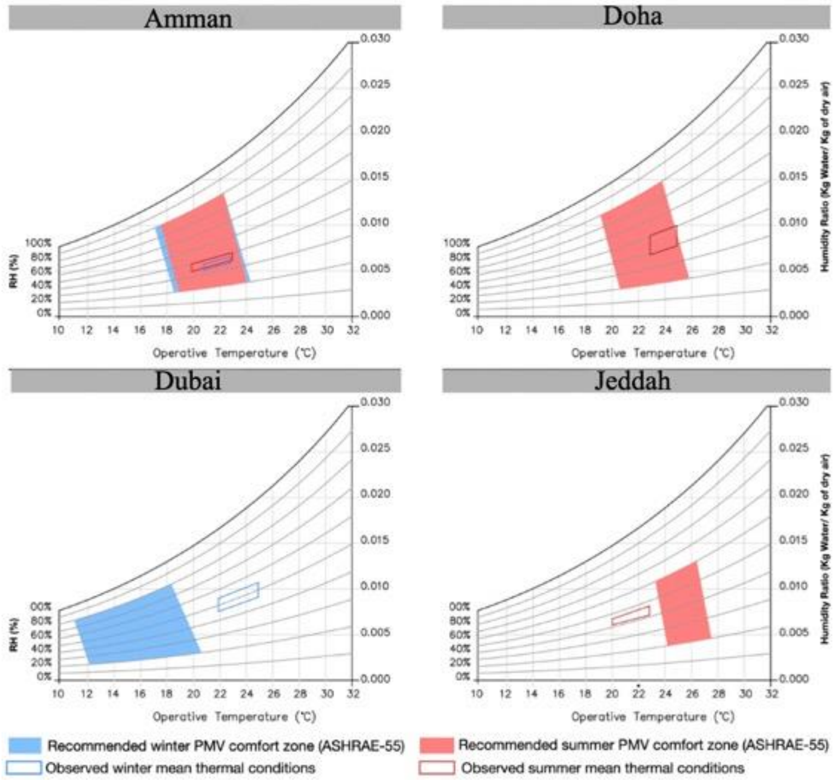

Figure 4.6 The observed thermal conditions for all surveyed buildings (outlined boxes) in Amman, Doha, Dubai, and Jeddah on psychrometric charts compared to the recommended thermal comfort zones (shaded boxes) provided by ASHRAE 55 standards (ANSI/ASHRAE 55, 2017), plots generated using the CBE tool (Schiavon et al., 2014).

4.9.2 Distribution of TSV and PMV

Table 4.6 illustrates the overall distribution of PMV and TSV during summer and winter, the votes being classified into three categories, i.e., hot, cold, and neutral (see section 4.8.5). In summer, while PMV predicted that 53% of votes would be in the neutral category, substantially below the 80% acceptability criterion specified by the ASHRAE 55 standard (ANSI/ASHRAE 55, 2017), TSV was even lower at only 41% votes falling into neutrality. Surprisingly, while PMV predicts 40% of votes would fall in hot discomfort, TSV shows an almost exact proportion (39%) falling into *cold discomfort*. In winter, while PMV predicted 78% votes to fall into neutral (i.e., almost meeting the acceptability criterion), only 35% TSV are actually comfortable, 48% subjects suggesting a sensation of warm discomfort. Amman and Doha perform differently to Dubai and Jeddah, due to the former group falling within the recommended standards (Figure 4.6).

Figure 4.7 shows the distribution of PMV and TSV based on the occupancy types. The average of PMV-hot was higher in office buildings and schools (average 35%), while it was negligible in mosques and hospital buildings. PMV-hot was higher in Doha offices compared to Amman offices, due to the variation in the operation mode, as five buildings out of thirteen in Amman have mixed-mode ventilation, contrary to Doha offices, that have no operable windows (see Appendix (b)). In mosques during winter, though PMV predicts neutrality for 97% of subjects, the majority of TSVs were on the warm side (Figure 4.7), this could be due to the high metabolic rate for prayers. In the hospital building, the PMV shows a cold state for 87% of subjects, and this was supported with 50% of observed TSV.

Table 4.6 The distribution of predicted PMV and observed TSV in all surveyed buildings in the four cities during summer and winter, the votes are classified into three categories (i.e., cold, neutral, and hot).

		PMV			TSV		
Season	Subjects (*n*)	Cold	Neutral	Hot	Cold	Neutral	Hot
Summer	677	7%	53%	40%	39%	41%	20%
Winter	356	5%	78%	17%	18%	35%	48%
Overall	1,033	7%	58%	35%	33%	40%	28%

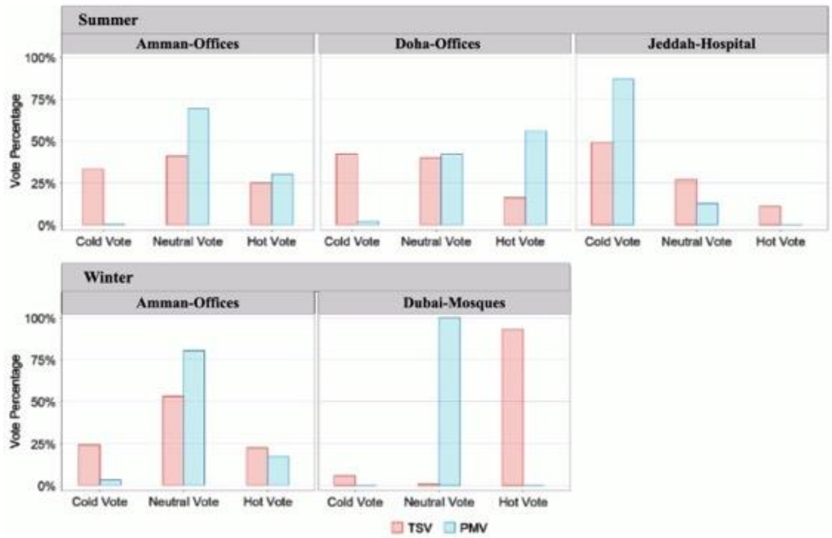

Figure 4.7 The distribution of observed TSV and PMV based on occupancy type and city during summer and winter, $n\_subjects = 1{,}033$, the subject votes are classified into three categories (i.e., cold, neutral, and hot).

4.9.3 Difference between TSV and PMV

Figure 4.8 shows the recorded indoor air temperature in each building in all surveyed cities across summer and winter. In summer, the indoor temperature ranged between 17.2 °C and 26.1 °C. In winter, we observe that the reported minimum indoor air temperature (20.2 °C, s = 0.9 °C) was higher than the reported temperature in summer. Further, to examine the differences in mean scores between the PMV and observed TSV in all surveyed buildings, we use the mixed-effects model to deal with the non-independence, as our sample has yielded 1,033 valid individual thermal comfort responses (i.e., TSV and PMV)[7], from four occupancy types, nd from four cities. The dependent variable was identified to be the difference between TSV and PMV (i.e., $\Delta\mu$ = TSV - PMV). The city, season, and building type were identified as predictors. In addition, building identity (ID) were included as a random effect, as there were multiple measurements from each building and analysis has to consider this clustering.

7 Dubai-summer data (n = 68) were omitted from the total number of dataset (n = 1,101) due to unavailable PMV, this resulted to reduce dataset to n = 1,033 (see section 4.8.3).

Results from mixed-effects model show that the only significant predictor found to be city [Δμ = -0.56, 95% CI = -0.93 to -0.19] thanks to mean temperatures being 0.56 °C lower in Doha than Amman. While season [Δμ = 0.19, 95% CI = -0.22 to 0.59] and building type [Δμ = 0.54, 95% CI = -0.12 to 1.20] were not significant predictors. Further, our analysis of the random effect shows that not all buildings were the same in each city, slight differences between all the individual buildings were observed. There were only three office buildings in Doha namely QO1 [Δμ = 0.01, 95% CI = 0.20 to 0.94]; QO8 [Δμ = -1.8, 95% CI = -0.96 to -0.15]; and QO9 [Δμ = -1.41, 95% CI = -0.78 to -0.05], where the difference between TSV and PMV appears to be significantly different from zero (Figure 4.9). Therefore, the cities differ significantly from one another, Doha has a lower mean score for (Δμ) compared to the other three cities. while no overall significant difference between summer and winter was reported.

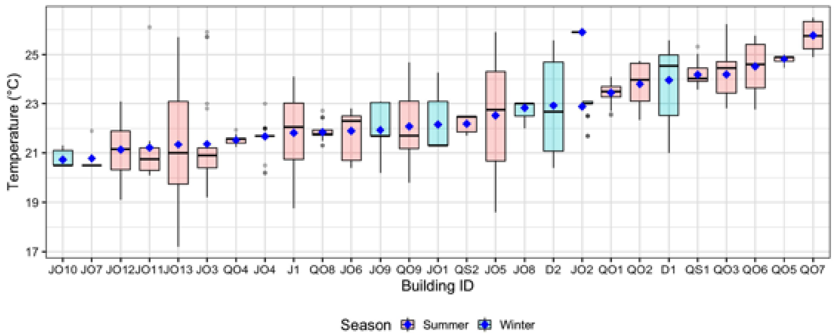

Figure 4.8 Ranked boxplots for mean indoor air temperatures for each building in the four surveyed cities in winter (blue) and summer (red), (each building has a unique ID, see Appendix B), whiskers indicate the minimum and maximum scores, black dots indicate outliers, blue square indicates mean score for each building.

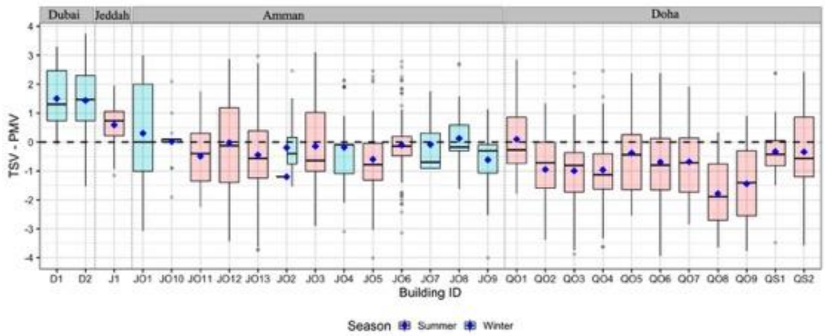

Figure 4.9 Boxplots for winter (blue) and summer (red) show the difference values between the observed TSV and predicted PMV (TSV - PMV) over all surveyed cities in each individual building during summer and winter, (each building has a unique ID, see Appendix B), whiskers indicate the minimum and maximum scores, black dots indicate outliers, blue square indicates mean score for each building, $n\_subjects = 1{,}033$.

4.9.4 Compare TSV to other thermal comfort models

The analysis in Section (4.9.2) has demonstrated that the PMV model results in indoor conditions that do not result in 80% acceptability. It is therefore pertinent to ask whether other thermal comfort models would fare better. Hence, here we present a systematic comparison between TSV and three extant thermal comfort models to investigate their applicability in predicting occupant's thermal sensation in the ME. The selected models are: (i) the predicted thermal sensation ($\mathrm{T_{sens}}$) by Gagge (Gagge et al., 1986), (ii) $\mathrm{PMV_g}$ that is Gagge's version of PMV (Gagge et al., 1986), and (iii) $\mathrm{PMV^*}$ which is similar to PMV except that is calculated using $\mathrm{SET^*}$ (Standard Effective Temperature) rather than operative temperature. $\mathrm{SET^*}$ is calculated using the surface temperature and skin wettedness (Ye et al., 2003). These models are acknowledged in the literature and used only in air-conditioned buildings.

Figure 4.10 shows the mean scores of all tested thermal comfort models and the TSV, with the latter has the lowest mean value (-0.12). To examine the difference between mean scores of all tested variables, a one-way ANOVA test was used. Result shows statistically significant differences between all means (F (4) = 337.5, p < 0.00), except the difference between means of $\mathrm{T_{sens}}$ and $\mathrm{PMV_g}$, was not statistically significant (Table 4.7), as suggested by the Post-hoc test. As we see from Table 4.7, the difference between mean of TSV and means of all thermal comfort models were statistically significant, with adjusted p-value < 0.001. This finding shows discrepancies between observed TSV and all tested thermal comfort models' predictions, though this is least between PMV and TSV.

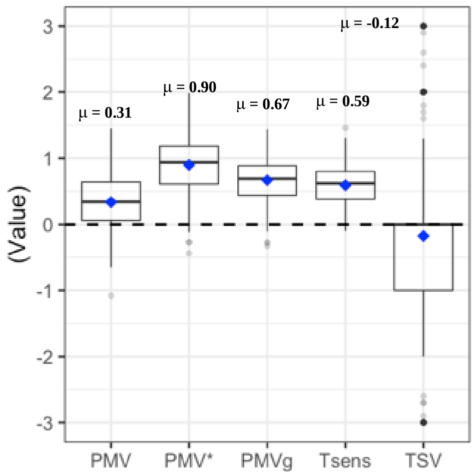

Figure 4.10 Boxplots show the differences in mean scores between the observed TSV and four thermal comfort models used in air-conditioned buildings, whiskers indicate the minimum and maximum scores, black dots indicate outliers, blue square indicates mean score for each variable.

Table 4.7 The reported results of Post-hoc test, *** indicates p < 0.00, n.s. indicates not statistically significant.

Difference of Levels	Difference of means	95% CI		Adjusted p-value
PMV* - PMV	0.57	0.48	0.65	0.00***
PMVg - PMV	0.33	0.25	0.42	0.00***
Tsens - PMV	0.26	0.17	0.34	0.00***
TSV - PMV	-0.51	-0.60	-0.42	0.00***
PMVg - PMV*	-0.23	-0.32	-0.15	0.00***
Tsens - PMV*	-0.31	-0.40	-0.22	0.00***
TSV - PMV*	-1.08	-1.16	-0.99	0.00***
Tsens - PMVg	-0.08	-0.16	0.01	0.11 n.s.
TSV - PMVg	-0.84	-0.93	-0.76	0.00***
TSV - Tsens	-0.77	-0.85	-0.68	0.00***

4.9.5 Thermal comfort in green buildings

To investigate whether green buildings in the ME improve subjects' thermal comfort compared to the occupant in non-green buildings, we compare the observed TSV to the predicted PMV in seven green buildings and 17 non-green buildings in Amman and Doha (Figure 4.11). Note that Figure 4.6 has already shown that all buildings in our sample in Amman and Doha are standards compliant, so the goal here to examine whether there is a difference in acceptability. The green buildings in Amman are both LEED and JGBG-certified, which rely on ASHRAE 55 standard recommended range for thermal comfort, while green buildings in Doha are designed to the localised GSAS, that defines particular thermal conditions for operation stage as illustrated in section 4.5. The *t*-test suggests statistically significant differences between mean scores of TSV and PMV in both building types in Amman and Doha (p-value < 0.05).

In non-green buildings, we observed that mean PMV was significantly higher than mean TSV, with differences of -0.33 and -0.75 in Amman and Doha, respectively. In green buildings, the differences between mean scores of PMV and TSV were also statistically significant and ranged between [-0.18, -1.32]. The difference was higher in green buildings in Doha compared to those in Amman. The majority of observed TSVs in buildings (i.e., green and non-green) in Doha were on the cold side. This result shows that green buildings that expected to provide better thermal environment for their occupants compared to non-green buildings have failed to do this. Further, result from green buildings in Doha questions the capability of the localised thermal comfort codes in improving occupant thermal comfort in the region.

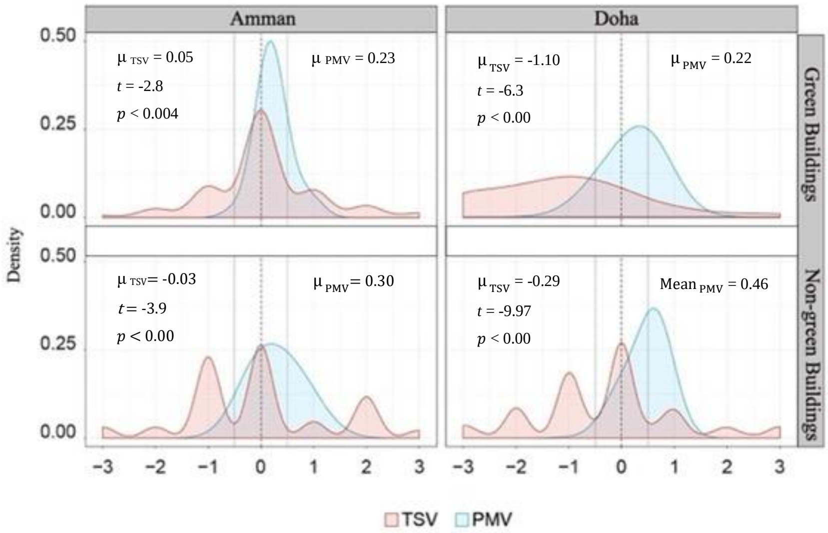

Figure 4.11 Comparison between the observed TSV and PMV in the certified-green buildings and non-green buildings in Amman and Doha. Green buildings in Doha are GSAS-certified and those in Amman are LEED + JGBG-certified, $n\_Amman = 502$, $n\_Doha = 377$, $n\_GB = 7$, $n_{non} - GB = 17$.

4.9.6 Neutral (comfort) temperature for the ME

We use linear regression to calculate the neutral temperature (T_n), based on TSV and PMV (see equation (7), (8), and (9)), T_n was calculated for each city separately. At the outset, the TSV and PMV were regressed with the indoor operative temperature (T_o) to predict the T_n. The observed TSV were binned in 1°C intervals (Albadra et al., 2017; Mishra & Ramgopal, 2015; Natarajan et al., 2015). The gradient of the linear regression (α) represents the temperature perturbation required for a one-unit change on the TSV scale, thus we can measure the subjects' sensitivity to changes in the indoor thermal environment (Albadra et al., 2017; Indraganti, 2010; Nguyen et al., 2012). Table 4.8 illustrates the gradient (α) and intercept (b) of the fitted linear models together with the p-value for the gradient and the coefficient of determination (R^2). Looking at Table 4.8, the $T_{n(PMV)}$ showed a varied range of temperatures; cooler comfort temperature of 19.62 °C in office buildings in Amman, moderate conditions of 20.66 °C in office buildings in Doha, and warmer perceptions of 25.42 °C in the hospital in Jeddah.

Likewise, $T_{n(TSV)}$ was calculated based on the observed TSV. In Doha and Jeddah, the R^2 generated from TSV were high (0.85 and 0.76 respectively), and T_o can hence be used as a good predictor to estimate T_n in these two cities (Table 4.8). In contrast, in Amman R^2 was low at 0.18 and hence too small to predict T_n. Therefore, T_n in Amman was instead predicted using Griffith's method (see equation (10)), which gives T_n = 21.96 °C. Results from mosque buildings in Dubai were not significant for both PMV and TSV (p-value > 0.05), thus T_n could not be predicted.Figure 4.12 shows the plotted regression lines of TSV and PMV against the T_o in the three cities, the mean neutral temperature is the point where the regression lines corresponding to mean PMV/TSV of zero. The gradient of the regression line for Doha and Jeddah (both α = 0.34 K) is steeper than those seen for other studies in the ME; 0.23 K in domestic buildings in Kuwait (Al-ajmi & Loveday, 2010a), 0.21 K in offices in Qatar (Indraganti & Boussaa, 2017) but the smooth gradient was found in air-conditioned mosques of 0.13 K (Al-ajmi, 2010a). The PMV predictions underestimated the observed neutrality in offices in Amman and Doha by about 2.34 °C and 4.08 °C respectively, while in hospital building in Jeddah, the PMV overestimated the observed neutrality by 2.78 °C. This may indicate that air-conditioning systems in hospital are operated in a way that does not consider the nature of nurses' job that requires to move around between patient rooms (higher activity levels). In contrast, employees in workplaces preferred warmer temperature due to their sedentary levels.

Table 4.8 Linear regressions of TSV and PMV versus operative temperature, T_o was binned into 1 °C interval, (* p < 0.05; ** p < 0.01; *** p < 0.001; n.s. indicates not significant). The results from Dubai study were not significant for both PMV and TSV, thus not presented in the table, $n\_Amman = 502$, $n\_Doha = 377$, $n\_Jeddah = 52$.

Index	Location	α(/°C)	b	R^2	p-value	T_n ± SE (°C)
PMV	Amman	0.165	-3.24	0.97	0.001***	19.62 ± 0.20
	Doha	0.125	-2.48	0.96	0.001***	20.66 ± 0.26
	Jeddah	0.304	-7.73	0.97	0.001***	25.42 ± 0.42
TSV	Amman[a]	-	-	0.18	0.20 n.s.	21.96
	Doha	0.341	-8.44	0.85	0.01**	24.74 ± 1.41
	Jeddah	0.342	-7.74	0.76	0.01**	22.64 ± 1.79

[a] [$T_{n(TSV)}$ for Amman is calculated using Griffith's method, that has no gradient and intercept. The reported value for Amman represents the mean value of observed nuetral temperatuure].

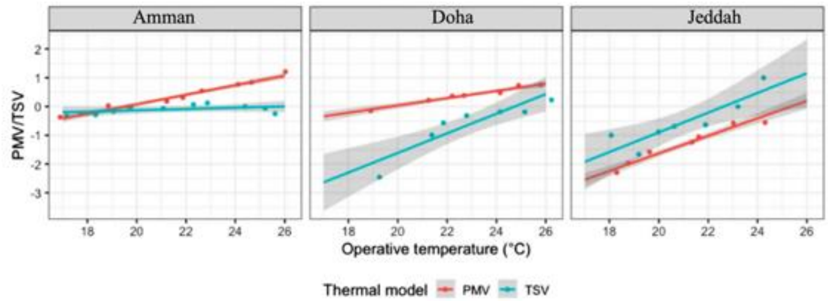

Figure 4.12 The relation between TSV and PMV with indoor operative temperature (T_o) in Amman, Doha, and Jeddah, each dot is a binned into 1 °C interval, so each dot represents several data points, $n\_Amman = 502$, $n\_Doha = 377$, $n\_Jeddah = 52$, (statistical analysis in

Neutral (comfort) temperature for the ME

We use linear regression to calculate the neutral temperature (T_n), based on TSV and PMV (see equation (7), (8), and (9)), T_n was calculated for each city separately. At the outset, the TSV and PMV were regressed with the indoor operative temperature (T_o) to predict the T_n. The observed TSV were binned in 1°C intervals (Albadra et al., 2017; Mishra & Ramgopal, 2015; Natarajan et al., 2015). The gradient of the linear regression (α) represents the temperature perturbation required for a one-unit change on the TSV scale, thus we can measure the subjects' sensitivity to changes in the indoor thermal environment (Albadra et al., 2017; Indraganti, 2010; Nguyen et al., 2012). Table 4.8 illustrates the gradient (α) and intercept (b) of the fitted linear models together with the p-value for the gradient and the coefficient of determination (R2). Looking at Table 4.8, the $T_{n(PMV)}$ showed a varied range of temperatures; cooler comfort temperature of 19.62 °C in office buildings in Amman, moderate conditions of 20.66 °C in office buildings in Doha, and warmer perceptions of 25.42 °C in the hospital in Jeddah.

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Table 4.8).

4.9.6.1 Energy saving scenario

Table 4.9 shows the results from the Energy Plus models for the calculated $T_{n(PMV)}$ and observed $T_{n(TSV)}$ and the potential reduction in the annual building energy demand. In the office building models in Amman and Doha, the annual building energy demand was reduced by 20% and 13%, respectively, while the reduction was smaller (1.5%) in the hospital building model in Jeddah. Most of the reduction in the office building models has resulted from the higher indoor temperature for cooling set point based on the observed $T_{n(TSV)}$ compared to the predicted $T_{n(PMV)}$. The estimated overall building energy demand for space cooling was reduced from 27.04 kWh/m^2 to 16.39 kWh/m^2 in office models in Amman, and from 60.71 kWh/m^2 to 49.87 kWh/m^2 in Doha (Table 4.8). While, in the hospital model, the reduction in cooling energy demand was very small (6.00 kWh/m^2). In all building models, the heating energy demand reduction was negligible, less than 1.0% of the total building energy demand reduction.

Table 4.9 Annual building energy demand for simulated models based on the proposed $T_{n(PMV)}$ and observed $T_{n(TSV)}$ in office buildings in Amman and Doha and hospital in Jeddah during cooling season. Note: other end uses for each model (e.g., lighting, equipment operation, water systems, humidification, heat recovery, fans, and refrigeration) are excluded from the table due to their small values (< 2.0 kWh/m^2).

Location	Amman			Doha			Jeddah		
Bldg. Type	Office building			Office building			Hospital		
End Use (kWh/m^2)	$T_{n(PMV)}$	$T_{n(TSV)}$	Diff	$T_{n(PMV)}$	$T_{n(TSV)}$	Diff	$T_{n(PMV)}$	$T_{n(TSV)}$	Diff
Heating	4.99	0.91	4.08	0.24	0.11	0.13	0.01	0.01	0.01

Cooling	27.04	16.39	10.66	60.71	49.87	10.84	77.81	71.81	6.00

4.10 Discussion

Since this study has two lines of evidence, we first discuss our independent results that are obtained from the new thermal comfort field surveys, then we pool them with results from the meta-analysis of the existing thermal comfort studies in the ME.

4.10.1 New field evidence

The energy demand for space cooling is the fastest-growing end-use in building sector, as it has tripled over the past twenty years between 1990 and 2020. In countries with extreme hot climate, such as the ME, it is expected that the energy demand for space cooling would triple by 2050. This growth rate in cooling energy demand needs to be alleviated, starting by a large-scale investigation to question the applicability of current codes that used to design the indoor thermal environment in air-conditioned buildings in the ME. There is a need to ensure that such codes promote occupant thermal comfort and simultaneously contribute to achieve the energy efficiency development scenario is targeted by this region. Thus, the present study was designed to collect evidence of whether the air-conditioned buildings in the ME comply with standards recommended ranges, and if so, whether they are found to be comfortable by their occupants.

Our findings showed that the monitored thermal conditions in the surveyed buildings in Amman and Doha (i.e., offices and schools) were within the ASHRAE 55 recommended comfort zone. While the recorded thermal conditions in buildings of Dubai and Jeddah (i.e., mosques and hospital) failed to be within the recommended limits. Overall, the PMV predicted that 58% of votes would be in the neutral category, and only 40% of subjects voted neutral, this is significantly below the ASHRAE 55 recommended value of 80% (ANSI/ASHRAE 55, 2017). Interestingly, during the cooling season, 39% of subjects through all surveyed cities expressed cold sensation, contrary to the PMV prediction that suggested 40% of subjects would feel hot, this was clearly observed in office buildings and schools.

In the hospital, the PMV prediction of cold discomfort for 87% of votes, was supported by 50% of the observed nurses' votes, which show cold state. This can be explained by three reasons: (i) nurses had a variety of metabolic rates with low clo (mean = 0.6) and this may affect their thermal sensation, especially during sitting with light work, (ii) the different requirements of thermal zones within hospital buildings, as nurses were surveyed at several locations at the inpatient wards nursing stations, and corridors (in front of patient rooms), these locations have no strict requirements within ASHRAE 170 standard for ventilation in health care facilities (ASHRAE 170, 2017) in terms of design temperature and relative humidity compared to other spaces, (i.e., patient rooms, intensive care units), and (iii) the HVAC system is optimised to provide cooler temperatures in the nursing stations, due to prior expectation considering the nature of nurses' job that required high metabolic rate. In the mosques, during heating season, PMV expected that 97% of votes would be in the neutral category, while 93% of subjects felt hot. This is possibly due to excessive heating in the praying halls designed to heat the entire volume during the winter. Taking into consideration that those attending prayers spend a maximum of 15 minutes in the mosque and had high metabolic rate (mean = 2.5), which could affect their thermal sensitivity.

The discrepancy between PMV and TSV was seen also between the recommended and observed neutral temperature. As our calculations for $\mathrm{T_{n(TSV)}}$ in air-conditioned office buildings in Amman and Doha were found to be 21.96 °C and 24.74 °C, which were comparatively higher than the predicted $\mathrm{T_{n(PMV)}}$ of 19.62 °C and 20.66 °C, respectively. In contrast, the $\mathrm{T_{n(TSV)}}$ in the hospital in Jeddah was 22.64 °C, lower than the $\mathrm{T_{n(PMV)}}$ of 25.42 °C, with difference of 2.87 °C. These findings encourage us to compute the potential reduction in the building energy demand for space cooling, assuming $\mathrm{T_{n(TSV)}}$ is used instead of the recommended temperatures by PMV. We find that a reduction in the annual building energy consumption of between 13% and 20% is possible in office buildings, whereas it is significantly lower in the hospital (1.5%). These reductions correspond to raising the indoor temperatures in office buildings by 4.08 °C in Doha and 2.34 °C in Amman.

From an economical perspective, raising the indoor temperature in office building in Amman by 2.3 °C may save 10.66 kWh/m^2 /year of space cooling energy demand, and since the Jordanian government priced the electricity at 0.18 JD/kWh (0.25 USD/kWh) for commercial sector (National Electric Power Company (NEPCO), 2020), this resulted in annual energy saving of 5,756 JD (8,118 USD) for the single unit that has an average floor area of 3000 m^2 .Likewise, adjustment the indoor temperature of 4.1 °C in the office building in Doha could cut the annual energy demand for space cooling by 10.84 kWh/maintain. This resulted in dropping the annual cost for space cooling from 30,500

QR (8,377 USD) to 25,000 QR (6866 USD), with annual saving of 5,500 QR (1,479 USD) per the single office building, considering the electricity in Qatar is priced at 0.20 QR/kWh (0.05 USD/kWh) (Qatar General Electricity & Water Corporation, 2020) and the building typical floor area is around 2,500 m^2, similar to buildings surveyed in this study.

In Qatar, the total annual energy demand for space cooling is around 14.7 TWh, with total annual cost around 5.5 billion QR (1.5 billion USD) (Saffouri et al., 2017), the total number of the commercial buildings over the last ten years is found to be around 9,518 units (Krarti et al., 2017). Hence the expected energy cost saving in commercial buildings based on our estimation is around 0.05 billion per year. This value constitutes 1.1% of the total annual electricity cost for space cooling in Qatar. It is worth mentioning that the cost of electricity tariffs in most of the ME countries, specifically in the Gulf Cooperation Council countries, i.e. Qatar are among the lowest in the world (Krarti et al., 2017), with substantial price subsidised by governments, this could be one of the reason behind the continuous energy demand growth in air-conditioned buildings in this region.

4.10.2 Pattern of thermal comfort across the ME

To gain an aerial perspective of the occupant thermal comfort trend across the ME, we aggregate the meta-analysis results from section 4.7 with our obtained results from the present study (section 4.9), thus we have a large scale dataset covering five countries, six different occupancy types, with a total of 2,649 subjects (see appendix (e)). Figure 4.13 (a) shows a forest plot for the calculated values of differences in mean scores between TSV and PMV (i.e., $\Delta\mu$) through the whole dataset. Most thermal comfort studies in the ME reported similar results regardless the building type or the location of the study, with the majority of difference values were on the negative side and ranged between [-0.18 and -0.81], i.e., mean scores of TSV were generally lower than mean scores of PMV. Indeed, the latter fail to predict the thermal sensation for 94% of subjects in this dataset.

However, two studies reported contrary results, i.e., the hospital and mosque buildings. These differences could be a result of several factors including the building design, the low thermal insulation level for patients and staff in hospitals and the high metabolic rate for prayers in mosques. Overall, this suggests that there is likely to be no “one size fits all” solution to resolving the differences between predicted and observed thermal comfort, with some building categories such as hospitals and mosques potentially needing further study.

Further, the tendency to over predict hot discomfort by the PMV model is likely resulting in an oversizing of cooling systems, this was reflected on the predicted $\mathrm{T_{n(PMV)}}$, which was generally lower than the observed $\mathrm{T_{n(TSV)}}$ with difference ranged between [0.4 °C, 4.1 °C] through all dataset (Figure 4.13. b). However, only in the hospital study, the difference was on negative side, which means subjects preferred lower indoor temperature than the delivered.

Overall, this robust evidence shows the gap between the current thermal comfort codes used in the ME and the actual occupant thermal sensation, also it offers evidence on the potential energy reduction in the air-conditioned buildings if more localised thermal comfort codes are enforced. Although there are emerging attempts by Middle Eastern countries, i.e., Qatar to develop local thermal comfort codes, it seems that these codes lack supporting evidence from any field survey as shown in section 4.9.5, despite the fact that GSAS requires a thermal comfort survey after occupancy as a compulsory credit (see section 4.5).

Similarly, other international thermal comfort models, i.e., $\mathrm{T_{sens}}$, $\mathrm{PMV_g}$, and $\mathrm{PMV^*}$ have failed in predicting occupant's thermal sensation, while they provided similar results to those yielded by the PMV model. Therefore, a thermal comfort paradigm shift that can effectively and assuredly offset the exponential increase in the space cooling energy demand, without compromising the occupant thermal comfort is timely and necessary in the ME. This would not only reduce energy consumption and hence carbon emissions (IEA, 2019a), but also improve overall health, well-being, and work performance (WGBC, 2016) by obviating the need to wear warm clothing indoors or the need to resort to secondary heating, which has been anecdotally observed in some buildings in our study.

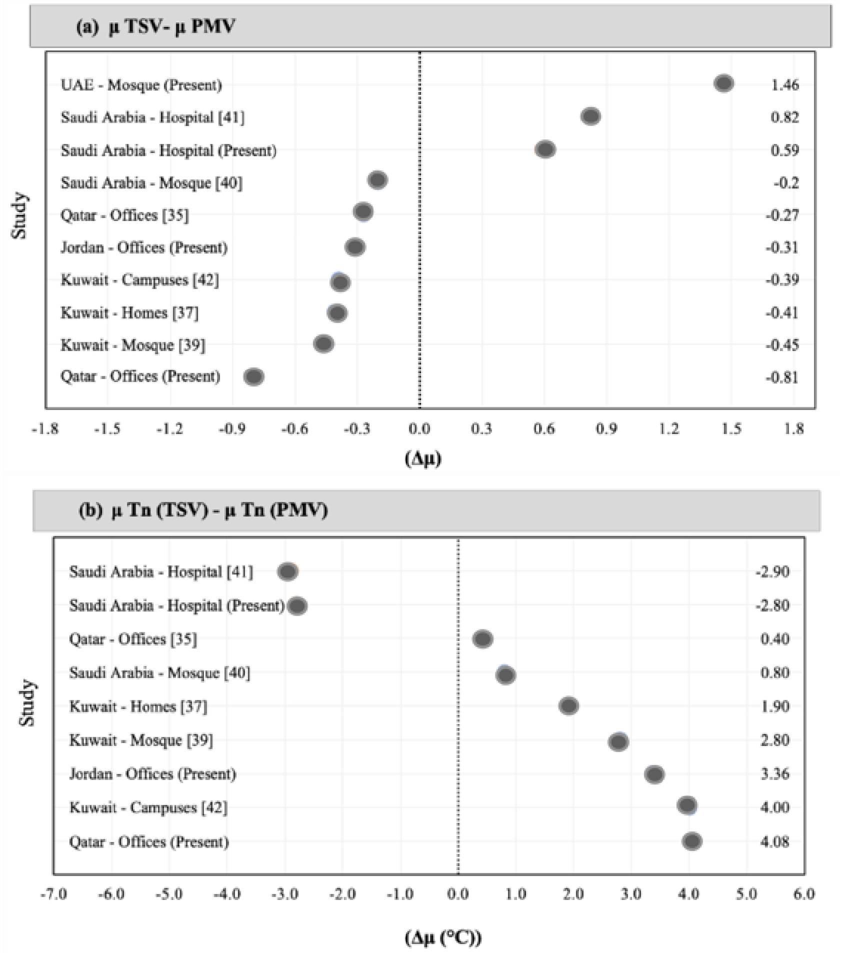

Figure 4.13 Forest plots from pooled analysis including the present study, (a) the difference between mean scores (i.e., Δµ = µ TSV- µ PMV) for each study, i.e. (Δµ > 0) indicates TSV is greater than PMV, (b) the difference between the observed neutral temperature $T_{n(TSV)}$, and predicted neutral temperature $T_{n(PMV)}$, through all datasets, $n = 2{,}649$, x-axis represents the standardised mean difference and vertical dotted line represents the value of no difference, studies are identified by country, building type, and reference.

4.11 Conclusions

In the Middle East, the international standards ASHRAE 55 and/or ISO 7730 are the de-facto industry tools used to design the indoor thermal environment in air-conditioned buildings. However, occupants' thermal comfort in these buildings is still questionable.

This study set out to investigate whether the air-conditioned buildings in the ME comply with standard recommended ranges for thermal comfort, and when they do, whether they are found to be comfortable by their occupants. From a meta-analysis using summary statistics of thermal comfort evidence in the ME, we demonstrate, for the first time, that the PMV model failed in predicting the occupant thermal sensation for 94% of occupants in five occupancy types (i.e., offices, homes, university campuses, hospitals, and mosques).

We produce a second, independent, line of evidence using large-scale thermal comfort field surveys of 1,101 subjects in 31 air-conditioned buildings within four countries in the ME that strongly supports the initial obtained findings. We show that the monitored indoor conditions in surveyed buildings were within the standard recommended range for 58% of the time, and only 40% of subjects found these conditions acceptable. We observe a gap between the expected thermal comfort and the observed subjects' thermal sensation during the cooling season. We find that 39% of subjects felt cold, contrary to the PMV prediction, which suggested 40% of subjects would feel hot. This is the reason for the large variation between the predicted $T_{n(PMV)}$ and the observed $T_{n(TSV)}$.

In office buildings in Amman and Doha, the $T_{n(TSV)}$ were found to be 21.96 °C and 24.74 °C, which were higher than those expected by PMV, at 19.62 °C and 20.66 °C respectively. Finally, we use the yielded data to estimate the potential reduction in the annual building energy demand for space cooling. We demonstrate that raising the indoor temperature in office buildings in Amman and Doha by 2.3 °C and 4.1 °C (i.e., based on the $T_{n(TSV)}$) has resulted in a reduction of 20% and 13% in the annual cooling energy demand, respectively. Overall, this study highlights the inapplicability of the "one size fits all" solution to overcome the gap between the predicted and observed thermal comfort. It shows also that most thermal comfort models that are used in air- conditioned buildings (e.g., PMVg, PMV*, and Tsens) are not suitable to predict subjects' thermal sensation in the ME. Further, it provides empirical data to be the basis for designers to develop a new and more localised thermal comfort model that considers the variations in subjects' thermal perception and mitigates the energy demand for space cooling without compromising the occupant thermal comfort in the ME.

4.12 Acknowledgment

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4.13 Funding

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4.14 Data Access statement

Data presented in this study are openly available https://doi.org/10.15125/BATH-00967

4.15 Appendices

(a) Thermal comfort survey with Arabic-dialects translation (Classical Arabic + Levantine-Arabic)

1. At present, I feel:

English	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Arabic-classic	بارد جدا	بارد	بارد قليلا	مرتاح	دافيء قليلا	دافيء	حار
Arabic-Levantine	بردان كتير	بردان	بردان شوي	مرتاح	مشوب شوي	دافي	كتير مشوب
	-3	-2	-1	0	+1	+2	+3

2. Your clothes at present: (Please tick)		3. What is your activity during the past 15 minutes? (Please tick)	
Short Sleeve shirt/blouse		Sitting (passive work	
Long sleeve shirt/blouse		Sitting (active work)	
Vest		Standing relaxed	
Trousers/long skirt		Standing working	
Shorts		Walking indoors	
Dress		Walking outdoors	
Pullover		Other………………	
Jacket			
Long socks			

short socks		
Tights		
Tie		
Boots		
shoes		
sandals		
head wear		
barefoot		

(b) Summary of surveyed buildings in this study; $n_{buildings} = 31; n_{subjects} = 1{,}101$. (M.M indicates mixed mode ventilation).

City	ID	Green certification	Sector	Operation mode	Bldg. type	Subjects (*n*)	Participant type
Amman	JO1	na	Private	M.M	Offices	26	Employees
Amman	JO2	na	Private	M.M	Offices	27	Employees
Amman	JO3	na	Private	M.M	Offices	37	Employees
Amman	JO4	na	Private	M.M	Offices	20	Employees
Amman	JO5	na	Private	M.M	Offices	10	Employees
Amman	JO6	Green	Private	HVAC	Offices	102	Employees
Amman	JO7	Green	Private	HVAC	Offices	24	Employees
Amman	JO8	Green	Private	HVAC	Offices	47	Employees
Amman	JO9	Green	Private	HVAC	Offices	45	Employees
Amman	JO10	Green	Private	HVAC	Offices	48	Employees
Amman	JO11	na	Private	HVAC	Offices	35	Employees
Amman	JO12	na	Private	HVAC	Offices	41	Employees
Amman	JO13	na	Private	HVAC	Offices	40	Employees
Doha	QS1	na	Public	HVAC	School	45	Staff
Doha	QS2	na	Public	HVAC	School	7	Employees
Doha	QO1	na	Private	HVAC	Offices	34	Employees
Doha	QO2	na	Private	HVAC	Offices	15	Employees
Doha	QO3	na	Public	HVAC	Offices	28	Employees
Doha	QO4	na	Private	HVAC	Offices	30	Employees
Doha	QO5	Green	Public	HVAC	Offices	26	Employees
Doha	QO6	na	Private	HVAC	Offices	67	Employees
Doha	QO7	na	Private	HVAC	Offices	30	Employees
Doha	QO8	na	Private	HVAC	Offices	74	Employees
Doha	QO9	Green	Public	HVAC	Offices	21	Employees
Dubai	D1	Design award	Public	HVAC	Mosque	23	Prayers
Dubai	D2	Design award	Public	HVAC	Mosque	79	Prayers
Dubai	S1	na	Public	HVAC	School	27	Staff
Dubai	S2	na	Public		School	10	Staff
Dubai	S3	na	Public		School	14	Staff
Dubai	S4	na	Public		School	17	Staff
Jeddah	H	Environment award	Public	HVAC	Hospital	52	Employees

(c) The instruments used to monitor indoor thermal conditions in surveyed buildings in the ME.

Instrument	Variable	Unit	Valid range	Accuracy
SWEMA (SWEMA, 2020)	T_g	ºC	[0, 50]	±0.1
	T_a	ºC	[10, 40]	±0.3
	RH	%	[0, 100]	±1.0

	V_a	ms^{-1}	[0.05, 1.0]	±0.03	
Delta 32.3 (Delta OHM, 2019)	T_g T_a RH V_a	ºC ºC % ms^{-1}	[-10, 100] [-40, 100] [0, 90] [0.1, 5]	±0.1 ±0.1 ±1.5 ± 0.2	
Heat stress wet bulb globe thermometer	T_g T_a RH	ºC ºC %	[0, 80] [0, 50] [1, 99]	±0.6 ±0.8 ±3.0	
Hot wire thermo-anemometer	V_a	ms^{-1}	[0, 25]	±0.01	

(d) Summary of the results in new dataset created using aggregated data from meta-analysis and our results in present study, the reported values represent the mean scores, (Present) indicates current thermal comfort studies done by the authors, T_n represents neutral temperature, $n_{subjects} = 2{,}649$.

Location	Source	Season	Subject (*n*)	Bldg. Type	μ(PMV)	μ(TSV)	$\mu T_{n(PMV)}$ (°C)	$\mu T_{n(TSV)}$ (°C)
Saudi Arabia								
	(Kotbi, King and Prasad, 2012)	Summer	281	Mosques	0.01	-0.19	21.5	22.3
	(Alotaibi *et al.*, 2019)		120	Hospital	-0.50	0.32	25.6	22.7
	Present		52	Hospital	-1.11	-0.52	25.42	22.64
Kuwait								
	(Al-ajmi and Loveday, 2010)	Summer	111	Houses	0.13	-0.28	23.3	25.2
	(Al-ajmi, 2010)		140	Mosques	0.19	-0.26	23.3	26.1
	(Al-ajmi, 2020)		136	Campuses	0.50	0.11	18.9	22.9
Qatar								
	(Indraganti and Boussaa, 2017)	Summer	828	Offices	0.04	-0.23	23.7	24.1
	Present		377	Offices	0.43	-0.38	20.66	24.7
Jordan								
	Present	Summer + Winter	502	Offices	0.30	-0.01	19.62	22.96

UAE								
	Present	Winter	102	Mosques	0.03	1.49	-	-

4.16 Postscript

This study aims to investigate the applicability of thermal comfort standards to design indoor thermal environment in air-conditioned buildings in hot environments, such as the ME. The results reported in this chapter show the following:

- There is a discrepancy between Fanger's PMV model prediction and the observed thermal sensation of occupants in air-conditioned buildings in the ME.
- During the cooling season, 39% of people felt cooler than the PMV model expected.
- Results also show a variation between the observed neutral temperature and the predicted comfort temperature by the PMV, which was higher with an average of 2.0 K in office buildings.
- This overestimation has resulted in an increase in the building energy demand for space cooling in the surveyed office buildings.
- Findings suggest a possible saving in cooling demand up to 20% if the indoor air temperature is raised by 4.0 K in the office buildings.

5 Conclusions

This thesis is concerned with the actual performance of IEQ in green office buildings at the operation stage in the ME. It has examined three interconnected research gaps, namely: (i) the role of GBCs in improving the performance of IEQ and enhancing occupant satisfaction with IEQ (ii) The design gap between the predicted performance and actual performance of IEQ in terms of thermal comfort and IAQ in green-certified office buildings, and (iii) the suitability of the applied thermal comfort codes to design indoor thermal environments in air-conditioned buildings, promote occupant thermal comfort, and save energy. To this end, three research questions were formulated and investigated in the contexts of the ME, the research questions were addressed as follows:

RQ 1. What is the actual role of localised GBCs in improving the performance of IEQ, occupant satisfaction, thermal comfort, and perceived health? This question was addressed in the first study (Chapter 2) by examining two objectives. I compare the performance of IEQ and its impact on occupant satisfaction and perceived health before and after moving to the first JGBG-certified building in Jordan. A longitudinal field study with repeated measures protocol was conducted, with the following key findings:

- Continuous monitoring in the surveyed buildings showed that 62% of monitored thermal conditions in the JGBG-certified building were within the standards specified limits, while only 48% of recorded thermal conditions in the CBs fell in this limit. There were statistically significant differences in T_a, T_r, RH, and V_a, between the JGBG-building and CBs, with a lower mean score in the JGBG-certified building. The monitored indoor CO_2 level in both building types had achieved the ASHRAE 62.1 recommended threshold for CO_2 of 1,100 ppm inside workplaces.
- Contrary to expectations, no improvement in the occupant satisfaction with IEQ was detected after moving to the GB, while three metrics, namely odour, glare and mental concentration were perceived to be significantly worse after moving to the GB. However, the overall mean score of occupant satisfaction with IEQ was comparable and below the neutral midpoint pre- and post-moving. Similarly, the mean score of occupant environmental concern was almost equal through both study phases.

- Another concerning outcome is that no significant differences were reported in the mean scores of all SBS symptoms pre- and post-moving to the GB. While the calculated percentage of occupants who experienced SBS symptoms for *some of the time* has increased 3 percentage points after moving to the GB. The prevalence of fever and flu symptoms had raised 10 percentage points after the transition. However, CBs and GB fail the ASHRAE 62.1 threshold of 20%, hence both building types could be labelled as "sick" buildings.
- Evidence of analysing occupant thermal comfort suggests that GB outperforms CBs, as the latter experienced an overcooling, with 40 % of occupants in CBs felt cold during summer, this was supported with 48% of occupants who preferred warmer indoor temperature in their workplaces.

Although the localised GBCs can play a vital role in cut down the energy bill, operation cost, and harmful impact of buildings on the environment, it seems that the lack of occupant physiological, psychological and health aspects in the IEQ requirements has curtailed occupant satisfaction and perceived health. The implications of these results are providing empirical evidence of the performance of localised GBCs in terms of IEQ, which may assist green building developers and policymakers in future green buildings developments. Further, the green building policies should account for the performance of buildings after occupation stage, which could be achieved by design a follow-up plan that covers the building and its users.

RQ 2. To what extent LEED office buildings in the Middle East achieve the specified minimum IEQ standards, after handover, and to what extent occupants of these buildings are satisfied and demonstrated better work performance? The second study (Chapter 3) examined the performance of the imported GBC, i.e., LEED standard, by comparing the performance of IEQ, occupant satisfaction and work performance in LEED-certified buildings and CBs. This investigation was essential after the yielded results from the first study, that suggested localised JGBG failed in improving the occupant perception and health. This study has identified the following findings:

- Although LEED office buildings in Jordan comply with LEED specifications of indoor CO_2 concentration levels and thermal comfort, the overall IAQ satisfied only 48% of the occupants.

- Interestingly, occupants in CBs had higher satisfaction with IEQ aspects (i.e., overall IAQ, ventilation, fresh air, and glare) compared to the occupants in LEED buildings.
- In CBs and LEED buildings, 61% and 58% of the occupants respectively reported IAQ, ventilation, and thermal comfort as the most important issues that needed improvement.

There are two main implications based on these results: (i) green building designers need to pay special attention to IAQ and ventilation since the current codes failed in improving occupant satisfaction with these two IEQ metrics. (ii) Results strengthen the idea that occupant feedback is as important as the objective measures when conducting the POE, as in many instances, subjective feedback reveals hidden concerns, which are hard to be detected using only objective assessment.

RQ 3. How suitable are international thermal comfort standards "including GBCs" for occupants in air-conditioned buildings in the ME? The last study (Chapter 4) examined whether the air-conditioned buildings in the ME complied with thermal comfort standards recommended limits, and when they do, whether occupants of these buildings are thermally comfortable. This study designed to test this in a large-scale thermal comfort study that covered different occupancy types within four countries in the ME. This study provides two lines of evidence, pooled results from a meta-analysis of the existing thermal comfort studies in the ME and dependant results from new seven field thermal comfort surveys. Here are the following key findings:

- The meta-analysis showed that during cooling season, the PMV Fanger's model failed in predicting the occupants' thermal comfort for 94% of the surveyed occupants in five occupancy types of air-conditioned buildings (i.e., office buildings, homes, hospital, mosques, and university campuses).
- Only 40% of surveyed subjects were in the neutral category, while PMV predicts 58% of subjects to be in the recommended thermal comfort zone. In the cooling season, 39% of the surveyed subjects express cold state discomfort, contrary to the PMV prediction for 40% of subjects would feel hot.
- Other examined thermal comfort models (i.e., PMV_g, PMV^*, and T_{sens}) provided the similar results to that obtained by PMV, and all models over predict the warm sensation of subjects.

- The observed neutral temperature in office buildings seen to be higher than the expected by PMV with difference range between [0.41 °C and 4.08 °C].
- Computer models showed a potential reduction in the building energy demand for space cooling up to 20% if the indoor air temperature is raised between 2.3 K and 4.0 K in office buildings.

These findings provide robust evidence of the gap between the current used thermal comfort standards in the ME and the actual occupant thermal sensation. Also, it shows that occupants in a hot climate region have a preference for warmer indoor thermal environment than delivered. Further, findings highlight the urgent need for more localised thermal comfort codes that improve occupant thermal comfort and assist in reducing the excessive space cooling in air-conditioned buildings in this region.

5.1 Future perspectives

Based on the obtained findings in this thesis, further research is required to test such recommendations made by the thesis. This research has thrown up many areas in need of further investigation as followings:

1. As shown in this thesis, there is a lack of systematic evaluation studies in green buildings, that covered the performance of IEQ and occupant perception, especially in the ME. Hence, more empirical research is required to validate the real performance of other green-certified building stock (e.g., residential, schools, and health care sector). This is critical for the future endeavour in green building design developments.
2. GBCs lack any uniform measures of the actual impact of IEQ on building users. Hence, there is a need to develop an evaluation tool, which can be used to assess the performance of IEQ and its impact on occupant’s perception and health during the operation stage. This tool could be integrated into the newly released GBCs version. This should assist in bridging the performance gap and assist in IEQ developments.
3. Using the current thermal comfort standards to design indoor thermal environments in air-conditioned buildings in the ME has resulted in uncomfortable occupants and excessive energy use for space cooling. Therefore, an essential next step in developing a new adaptive model, that significantly extends the range of acceptable indoor conditions. This could assist in saving

more energy in air-conditioned buildings in this region. Developing this model requires enhancing the current thermal comfort database in the ME and considering the future climatic condition changes.

All afore-mentioned aspects serve as items of future agenda for green building-related research.

5.2 Final remark

Do green-certified buildings in the ME meet the requirements of thermal comfort and IAQ that specified by GBCs? and if so, to what extent they are improving the occupants' satisfaction, perceived health, and work performance compared to the occupants in conventional buildings?

Recalling the underpinning question of this work, it has shown that the gap between design estimation and effective performance of IEQ in green-certified buildings is a topic that requires timely attention.

Green building standards and buildings' regulations attempt to move occupants towards neutral acceptable environments, whereas the standards average users are not existing because there are several individual differences (e.g., biological, physical, and psychological) that can play a role in the occupants' perception.

The role of green building certifications in improving the physical performance of IEQ and occupants' perception was evaluated in the office buildings. This work also focused on evaluating the suitability of current thermal comfort codes to design indoor thermal environments in air-conditioned buildings in hot environments such as the ME.

Evidence demonstrated that occupants of conventional buildings showed higher satisfaction with most IEQ aspects (overall IAQ, thermal comfort, ventilation) than occupants of green-certified buildings. Thus, green building certification schemes could benefit from stricter criteria for indoor air quality, ventilation, and thermal comfort.

Far from being a criticism of the international or localised building codes, studies such as that presented in this thesis can provide evidence-based data to improve the standards achieved in green building certification, whereas the emphasis given to energy should not come to the detriment of IEQ and occupant satisfaction.

Further, results obtained from this thesis could be applied to other modern office buildings that are built in recent times and share the same design approaches i.e., sealed envelopes with no operable windows. Such type of buildings is common in the ME, due to the harsh climate conditions and the desire to improve the building energy performance.

Appendix A
Are green buildings doing enough? the role of green certification and gender on sick building syndrome

A.1. Preamble

One of the promised benefits of green buildings is providing healthier and more comfortable indoor environments for their occupants. However, there is a growing concern that green buildings could reduce the occupants' perceived health and increase the prevalence of sick building syndrome symptoms. For example, poor air quality, insufficient ventilation, and the lack of control over air temperature and lighting can negatively affect occupants' perceived health. Hence, in this chapter, I compared the perceived health of occupants working in green-certified office buildings to occupants working in conventional office buildings. Further, since other factors could affect the perceived health, in this chapter I examine the role of gender differences on the prevalence of sick building syndrome. This chapter is in line with the research is presented in Chapter 3.

A.2. Declaration of authorship

This declaration concerns the article entitled:			
Are Green Buildings Doing Enough? The Role of Green Certification and Gender on Sick Building Syndrome			
Publication status (tick one)			
Submitted ☐	In review ☐	Accepted ☐	Published ☑
Manuscript reference			

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Candidate's contribution to the paper (%)
• Formulation of ideas: R. Elnaklah (80%) and S. Natarajan (20%). • Design of Methodology: R. Elnaklah (80%) and S. Natarajan (20%). • Data Collection: R. Elnaklah (100%). • Data Analysis: R. Elnaklah (90%) and D. Fosas (10%) • Presentation of data in journal format: R. Elnaklah (80%) and Natarajan (20%).

Statement from Candidate	
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.	
Signed: Rana Elnaklah	**Date** 30th Nov 2020

A.3. Abstract

One of the promised benefits of green buildings is providing healthier indoor environments for their occupants, however, this notion is still debated. To test this, a sample of 502 office-based workers from 13 air-conditioned office buildings (44.4% female and 55.6% male) in Jordan completed a questionnaire on Sick Building Syndrome (SBS) symptoms. The role played by gender in symptom-reporting was also investigated. Findings showed that building type made no significant difference to the prevalence of all SBS symptoms except the tiredness symptom which was slightly higher in the occupants of conventional buildings. Surprisingly, green buildings and conventional buildings had a higher occurrence of SBS symptoms than what industry standards allow for (up to 20%), suggesting that both building types would be classified as sick buildings.

Results have also shown that the only significant difference between male and female workers was in the cough and sore throat symptom, which was reported more often by female workers. These findings reinforce the need for further attention to the occupants' perceived health in the green buildings, which may use as an indict of the building performance.

A.4. Introduction

There is an increasing interest in how the Indoor Environment Quality (IEQ) of the green building promotes occupants' health, productivity, and satisfaction (WGBC, 2014), particularly in office buildings, where employees spend about a third of their time at the workplace. This is could be an important issue considering that prolonged exposure to environments with poor IEQ parameters (e.g., air quality, lighting, thermal comfort, and acoustic) could lead to the well-known Sick Building Syndrome (SBS). According to a definition provided by the World Health Organization (WHO), the SBS is a group of medical symptoms that affect buildings' occupants and linked to the time spent in the building, and usually disappear when the person is away from the building [2].

The benefits of the green building design are not limited to reduction in the energy consumption and the subsequent harmful impact on the environment, they can also include potential benefits of creating a healthier indoor environment for occupants (WGBC, 2016). There is an increasing concern of whether green buildings deliver a healthier indoor environment they promised or rather, they increase the prevalence of SBS compared to conventional buildings (Yudelson and Meyer, 2013).

To date, the research evidence on the effect of green buildings on the frequency of SBS symptoms is limited and equivocal. Although the study by Tham et al. in Singapore showed that the occupant perception of IEQ was slightly higher in the green building compared to the non-green building, no statistical differences in the proportion of SBS symptoms were found between the two occupants groups, also, the number of sick leave days was similar in both building types (Tham, Wargocki and Tan, 2015). In contrast, a pre- and post-evaluation study in the United States showed an improvement in the employees' perceived health and reduction in the self-reported absenteeism after moving to the green buildings (Singh *et al.*, 2010).

However, building physical features such as ventilation, lighting, temperature, etc. are not the only reasons behind the prevalence of SBS. Other psychological and physiological factors like job satisfaction, work-related stress, and gender differences might be as important in predicting SBS symptoms (Rostron, 2008). Of these, the effect of gender differences on the prevalence of SBS is still debated.

Several attempts had been made to clarify the role gender differences might play in explaining changes to the frequency of SBS symptoms reported by occupants. Findings suggested that female workers usually reported higher levels of SBS symptoms (e.g., fatigue, headache, irritated eyes or nose, cough, and dry skin) compared to male workers (Brasche *et al.*, 2001; Bakke *et al.*, 2007; Aries, Veitch and Newsham, 2010). This might be due to three factors are namely biological (e.g., genes, hormones, and metabolism), behavioural (e.g., smoking, diet), and social (e.g., stress, social network) (Rostron, 2008). Unfortunately, other researchers did not consider gender as a predictor for the frequency of SBS symptoms, missing the opportunity to clarify whether this is indeed the case or not (Norback and Edling, 1991; Kinman and Griffi, 2008).

Given the uncertain evidence concerning the role of green certification and gender differences on SBS, this paper aims to answer two questions, which are studied from a holistic perspective that accounts for both factors the physical (i.e., building type) and physiological (i.e., gender differences) that underpin SBS prevalence, the two questions are:

1. Do occupants in the green office buildings have a lower prevalence of SBS symptoms compared to their counterparts in the conventional buildings?
2. Do gender differences affect the prevalence of SBS symptoms in the workplace?

A.5. Methods

To answer the two questions, the data collection campaigns were designed to gather the responses of occupants in green and non-green office buildings, each of which has a random proportion of self-identified male and female employees. The dataset sample in this study reflects 502 responses from full-time office-based employees. The participants were selected randomly from five green buildings (n=261 respondents) and eight conventional buildings (n=241 respondents). Surveyed buildings are in Amman, the capital city of Jordan. All buildings are offices occupied by the private sector and did not report any known indoor air quality issues previously. The data were collected between summer 2017 – winter 2019.

A.5.1. Survey

The questionnaire was adapted from the Health and Work Performance Questionnaire produced by World Health Organization (WHO HPQ) (Kessler, Petukhova and McInnes, 2007). It consists of two sections, the socio-demographic to collect information from employees on potential covariates (e.g., age, gender, work experience, job role, weight, and height). The second section includes ten questions to assess the prevalence of SBS, these questions were classified into three groups based on the WHO classification of SBS symptoms (Figure 0.1).

Respondents were asked to rate the frequency of SBS symptoms during the 28 days preceding the survey date. A 5-point Likert scale was used per question (Garland, 1991). The scale ranged between 'not at all', 'a little of the time', 'some of the time', 'most of the time', 'all the time'. Further, the frequency of each symptom was compared to the ASHRAE standard 62.1 threshold (ANSI/ASHRAE 62.1, 2010). According to this standard, a building can be labelled as sick when 20% or more of its occupants reported discomfort symptoms linked to the time spent in the building for a period exceeding two weeks.

The paper-based survey was used. The questionnaire was designed and wrote originally in English, then translated to Arabic, the first language of most participants. Both versions of the questionnaire were combined with the consent form and distributed in the selected buildings during working hours between 0900 – 1700. Of the 502 participants, 55.6 % were Male and 44.4 % were female.

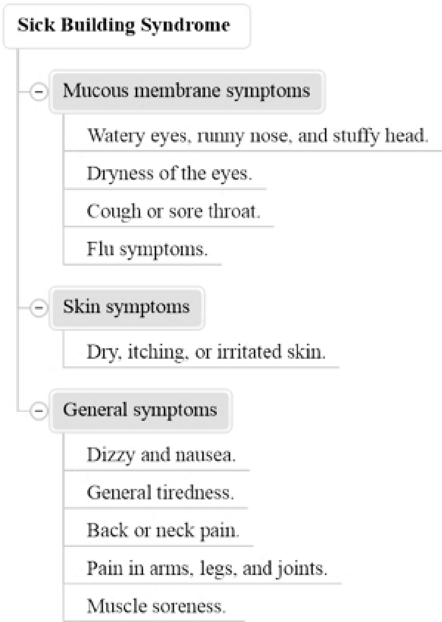

Figure 0.1 The categories of sick building syndrome symptoms.

A.5.2. Data Analysis

Each of the two research questions can be translated into the following questions: are the overall median prevalence of SBS symptoms the same between the two groups under consideration? Where the median is taken as an indicator of the overall change in self-reported SBS symptoms and the two groups under consideration refer to the conventional and green building types or male and female workers when addressing potential differences due to employees' self-reported gender. Each question is studied through the following analysis methods:

- Graphical inspection: A normalised stacked bar-chart of the response counts for each category and question, split by the variable of interest, should reveal any differences through the relative offset of the stacked bar of a group over that of the other.
- Statistical hypothesis testing: We have conservatively chosen to appraise medians since responses to the questions in the survey are Likert items. To this end, the

non-parametric Mann-Whitney U test (Wilcoxon's rank-sum test) is used to test the null hypothesis of no differences between groups at the 0.05 significance level.

- Analysis of effect size: Coherently with the numerical analysis based on medians, the Rank Biserial Correlation (RBC) (Guttman, 1956) was chosen as the measure of effect size, i.e. quantification of the magnitude of the difference between any two groups, regardless of their statistical significance. Similarly, to other correlation coefficients, the value of RBC is within [-1, +1], where 0 indicates no correlation, +1 a (perfect) positive correlation, and -1 a (perfect) negative correlation.

These were possible thanks to the following open source software: R (R Core Team, 2019), including the Tidyverse family (Wickham *et al.*, 2019) and HH libraries (Heiberger and Robbins, 2014), and Python (Python Software Foundation, 2020), including Numpy (Oliphant, 2006), Pandas (McKinney, 2010) and Pingouin (Vallat, 2018) libraries.

A.6. Results and Discussion

This section presents the results of the analysis of the impact of the green certification and gender differences on the SBS prevalence in workplaces, and it discusses the findings.

A.6.1. Building type and SBS

Figure 0.2 shows the breakdown of the scores for each SBS symptom in both building types. The occupants in the conventional buildings had a higher prevalence in most of SBS symptoms compared to the occupants in the green buildings. Moreover, from

Figure 0.2 we can see that more than 20% of the participants in both building types experienced six SBS symptoms for 'some of the time', these symptoms are namely watery eyes, neck pain, arms, legs and joints pain, muscle soreness, eye dryness and stuffy head, and tiredness (see section A.10). Compare this finding to the ASHRAE standard 62.1 threshold, both building types in this study would be classified as sick.

Table A.1 shows the results of the Mann-Whitney U test, which fails to reject the null hypothesis of no difference between the median scores according to the building type for nine SBS symptoms (In cases *p*-value > 0.05). While the U test suggests rejecting the null hypothesis of no difference between the median response according to the building type for tiredness symptom (U=27490.5, *p*-value < 0.01, RBC = 0.12), which was higher between the occupants in the conventional buildings.

This outcome is contrary to that of Tham et al. (2015) who reported no significant difference in the frequency of SBS symptoms between the occupants of the green and non-green buildings in Singapore, while both building types were below the recommended threshold (Tham, Wargocki and Tan, 2015). This discrepancy could be attributed to the cultural and personal variances (Norback, Torgen and Edling, 1990; Runeson *et al.*, 2004) or due to the differences in the buildings' characteristics (Skyberg *et al.*, 2003).

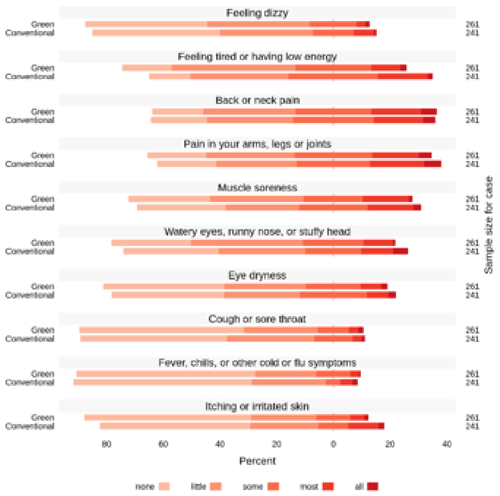

Figure 0.2 Breakdown of responses to SBS symptoms questions according to the building type (statistical analysis in Table A.1).

Table A.1 Statistical analysis of individual SBS questions according to the Mann-Whitney U test (n Green=261, n Conventional=241); GB indicates green buildings and CB indicates conventional buildings.

	μ		Δμ				
SBS Symptom	GB	CB	GB -CB	U	Tail	*p*-value	RBC
Dizzy	1	1	0	31475.0	Greater	0.49	≈0.00
Tired	1	2	-1	27490.5	Less	<0.01	0.12
Back or neck pain	1	2	-1	31957.5	Less	0.62	-0.02
Pain in arms, legs, or joints	1	2	-1	30264.0	Less	0.22	0.03
Muscle soreness	1	1	0	30851.0	Greater	0.64	0.01

Watery eyes, runny nose, or stuffy head	1	1	0	31227.5	Greater	0.55	≈0.00
Dryness of the eyes	1	1	0	29869.5	Greater	0.84	0.05
Cough or sore throat	0	0	0	29605.5	Greater	0.89	0.05
Flu symptoms	0	0	0	31753.0	Greater	0.41	-0.01
Dry, itching or irritated skin	0	0	0	29040.5	Greater	0.95	0.07

A.6.2. Gender differences and SBS

Figure 0.3 shows the results of the breakdown for the scores of SBS symptoms according to the occupants' gender. The female workers tend to have a higher frequency of SBS symptoms compared to the male workers for all symptoms except two symptoms are namely dizzy and watery eyes, runny nose and stuffy head, that were reported more often between male workers.

Table A.2 shows the results of the Mann-Whitney U test which fails to reject the null hypothesis of no difference between the median responses according to the occupants' gender for all SBS symptoms (In cases p-value > 0.05) except the cough and sore throat symptom (U=26960.5, p-value < 0.01, RBC = 0.13), which has a negligible effect size.

This finding is consistent with other studies in this area that found the gender differences is small and inconsistent in the self-reported symptoms (Kinman and Griffi, 2008). Also, the differences between male and female workers in SBS were observed to be reported frequently in particular symptoms included cough, sore throat, fatigue, and eye irritation (Bakke *et al.*, 2007), this variance can be attributed to the biological and behavioural differences.

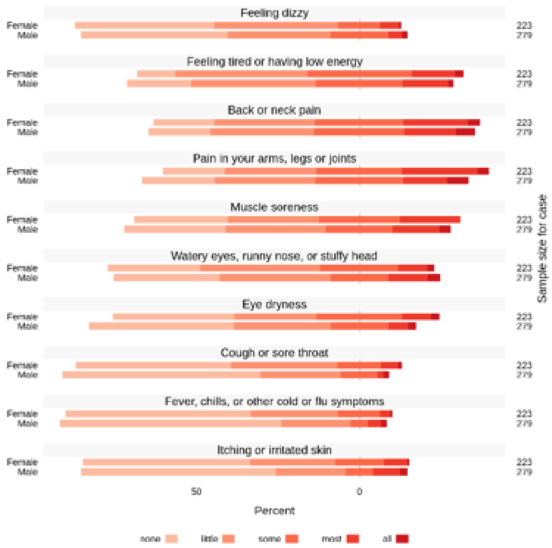

Figure 0.3 Breakdown of responses to SBS symptoms questions according to gender differences (statistical analysis in Table A.2).

Table A.2 Statistical analysis of individual SBS questions according to the Mann-Whitney U test (n Female = 223, n Male = 279); F indicates female subjects and M indicates male subjects.

	μ		Δμ				
SBS Symptom	M	F	M-F	U	Tail	*p*-value	RBC
Dizzy	1	1	0	31238.5	Greater	0.47	≈0.00
Tired	1	1	0	28498.0	Greater	0.96	0.08
Back or neck pain	1	2	-1	30740.5	Less	0.41	0.01
Pain in arms, legs, or joints	1	2	-1	28826.0	Less	0.07	0.07
Muscle soreness	1	1	0	29961.0	Greater	0.77	0.04
Watery eyes, runny nose, or stuffy head	1	1	0	30631.0	Greater	0.62	0.02
Dryness of the eyes	1	1	0	27601.5	Greater	0.99	0.11
Cough or sore throat	0	1	-1	26960.5	Less	<0.01	0.13
Flu symptoms	0	0	0	27612.5	Greater	0.99	0.11
Dry, itching or irritated skin	0	0	0	28835.0	Greater	0.94	0.07

A.7. Conclusion

This study investigated if the occupants of green office buildings in Jordan have a lower prevalence of SBS symptoms compared to those in the conventional buildings. It investigated as well if gender differences play a role in the frequency of SBS symptoms. The findings of our analysis based on 502 office occupants show that building type made no significant difference to the frequency of all SBS symptoms except the tiredness symptom, which was found to occur more often between the occupants of conventional buildings.

However, according to the ASHRAE standard 62.1 threshold, both building types can be classified as sick buildings, as more than 20% of their occupants had experienced six SBS symptoms '*some of the time'* during 28 days preceding the survey. Also, the present analysis indicates that female and male office workers reported the same frequencies for most of SBS symptoms, with a statistically significant higher prevalence of cough and sore throat symptom between the female workers albeit of negligible effect size. However, this study had a cross-sectional research design, and an absolute conclusion of causation cannot be made, thus longitudinal with repeated measures could assist in capturing any differences between the two samples.

Overall, our findings highlight a clear problem in the office buildings in Jordan and suggest that architects, designers, and building owners need to pay further attention in the future to the unintended consequences of green office buildings, that could potentially impose on employee health and affect the work performance and the financial return of the business.

A.8. Acknowledgments

This research is funded by Al-Ahliyya Amman University in Jordan "International Grants Program". The authors would like to thank Mr Mualla for helping with the data collection, Dr Ian Walker for helping in the design of the questionnaire, and the management of the surveyed buildings for allowing the authors to conduct the study.

A.9. Disclosure Statement

The authors reported no potential conflict of interest.

A.10.Appendix

The percentage of occupant response for each SBS symptom in both building types during 28-day preceding the survey

	None of the time		Little of the time		Some of the time		Most of the time		All the time	
SBS Symptom	GB	CB	GB	CB	GB	CB	GB	CB	GB	CB
Dizzy	43%	45%	36%	33%	17%	15%	3%	7%	15%	1%
Tired	17%	15%	44%	34%	27%	32%	10%	17%	2%	2%

Back or neck pain	18%	20%	33%	30%	27%	29%	18%	17%	5%	4%
Pain in arms, legs, or joints	21%	21%	31%	28%	28%	26%	16%	19%	4%	6%
Muscle soreness	29%	31%	33%	26%	21%	24%	16%	16%	1%	2%
Watery eyes, runny nose, or stuffy head	28%	33%	39%	31%	21%	20%	10%	11%	1%	5%
Dryness of the eyes	43%	39%	29%	27%	20%	24%	7%	7%	2%	2%
Cough or sore throat	58%	51%	26%	31%	11%	14%	3%	3%	2%	1%
Flu symptoms	63%	63%	21%	26%	12%	5%	3%	4%	0	2%
Dry, itching or irritated skin	59%	53%	23%	24%	12%	11%	5%	11%	1%	2%

A.11. Postscript

This chapter investigated whether green certification could reduce the prevalence of SBS symptoms reported by employees. Also, the role of gender differences in self-reported SBS symptoms was examined. The comparison between the occupants of green-certified buildings and conventional buildings shows that no difference in self-reported SBS was observed between the two building categories. Surprisingly, both building types did not meet the ASHRAE 62.1 threshold, thus they can be classified as ‘sick’ buildings.

Further, findings indicate that male and female employees in all surveyed office buildings have a similar frequency of all investigated SBS symptoms, except cough and sore throat symptom that was statistically higher between female workers. This chapter highlights a clear concern in the modern office buildings in general and green-certified buildings in particular, as such buildings are designed and built to deliver a healthier indoor environment for employees, whereas they show the opposite during the operation stage.

Appendix B

A comparison of indoor air quality and employee absenteeism in ‘local’ and ‘imported’ green building standards

B.1. Preamble

Several countries in the developing world have produced their localised GBCs, that suit the specific needs of the region. However, it has been argued that such codes could work better compared to the imported GBCs like LEED or BREEAM. Jordan as one of the developing world has developed the localised JGBG to replace the international LEED, which is commonly used to certify green buildings in Jordan. However, no systematic evaluation of the performance of the new localised code has been done. Further, no existing evidence of whether the localised JGBG superior to the imported LEED. Thus, in this chapter, we compare indoor air quality and absenteeism rates between two types of green buildings: JGBG-certified and LEED-certified. This chapter is supporting the investigation presented in Chapter 2.

B.2. Declaration of authorship

This declaration concerns the article entitled:
A Comparison of Indoor Air Quality and Employee Absenteeism In ‘Local’ And ‘Imported’ Green Building Standards
Publication status (tick one)
Submitted ☐ In review ☐ Accepted ☐ Published ☑
Manuscript reference
R.A. Elnaklah, S. Natarajan, A comparison of indoor air quality and employee absenteeism in ‘local’ and ‘imported’ green building standards, in: Indoor Air Quality, Ventilation and Energy Conservation in Buildings, Bari, Italy, 2019: pp. 42–89. https://doi.org/10.1088/1757-899X/609/4/042089.

Copyright status (tick the appropriate statement)
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Candidate's contribution to the paper (%)
• Formulation of ideas: R. Elnaklah (80%) and S. Natarajan (20%). • Design of Methodology: R. Elnaklah (80%) and S. Natarajan (20%). • Data Collection: R. Elnaklah (100%). • Data Analysis: R. Elnaklah (80%) and S. Natarajan (20%) • Presentation of data in journal format: R. Elnaklah (80%) and S. Natarajan (20%).
Statement from Candidate
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.
Signed: Rana Elnaklah **Date** 30th Nov 2020

B.3. Abstract

Buildings are responsible for a quarter of global carbon emissions. In the developing world, the desire to reduce energy consumption initially resulted in the adoption of 'imported' standards such as LEED and BREEAM and, over time, the development of several 'localised' standards that either supplant or compete with the imported standards. However, such standards have often been implicated in the unintended consequence of reduced indoor air quality resulting from lowered ventilation rates, in turn affecting employee productivity and absenteeism. Here, we systematically review and compare the performance of office buildings built to the localised Jordanian Green Building Guide (JGBG) and the well-known international LEED standard. We measure building performance in terms of the indoor air quality (via CO_2 concentration) and occupant absenteeism during winter 2019. Results show that the JGBG building had a significantly lower mean indoor CO_2 concentration than the LEED building during working hours ($p < 0.00$). In addition, the occupants in the JGBG building reported 20% more working hours ($p < 0.03$) and approximately 9 hours less of absolute absenteeism. These initial

results suggest that further development of localised codes is likely to bring greater benefit to the performance of building and occupants compared to imported standards.

B.4. Comparison between Jordanian Green Building Guide and LEED

In 1998, the U.S. Green Building Council (USGBC) produced the Leadership in Energy and Environmental Design (LEED) Green Building Rating System. LEED encompasses more than 90,000 registered buildings in the US and 165 countries, it coverers 2.2 million m² of projects area every day [1]. Recently, several countries, particularly in the developing world, have started to develop their own rating systems that address specific regional needs (e.g., climate, socio-economic, and cultural) [2]. The Pearl Rating System (PRS) in the United Arab Emirates, Qatar Sustainability Assessment System (QSAS) in Qatar, and ARZ Building Rating System in Lebanon are good examples of green assessment tools in the Middle East, which consider local needs.

Jordan as part of the Middle Eastern countries has experienced several phases of green building developments, which are presented chronologically in Figure 0.1, with LEED being the most common. According to the Jordanian Green Building Council (2019), Jordan has 21 registered buildings and seven certified buildings by LEED in the commercial sector [3]. In 2013, the Jordanian Green Building Guide (JGBG) was produced to replace the international rating system gradually. JGBG is a voluntary rating system available for everyone to use and is connected to an incentive scheme put forth by the Jordanian government [4].

Despite common targets and approaches to the issue of sustainability assessment with LEED, JGBG's structure, indicators, and metrics were developed independently. JGBG has four categories that are classified according to the building type: single residential, multi-residential, commercial/offices, and educational. Each category includes two subcategories, either conditioned or free running, and each has its own assigned points [4]. The number of points collected for each style of building indicates the degree of building's sustainability, which is divided into four classifications: A, B, C, and D. Table 0.1 compares the main attributes of LEED and JGBG. Closer inspection of the Table shows that JGBG consists of six main parameters; five of them are in common with LEED but with different weight for each parameter depending on the local priorities. LEED's 'innovation' and 'recycling and pollution' categories are absent in JGBG while it adds the ‘building management’ as a sixth parameter that is concerned with the overall performance of building post-handover.

The relative weights for energy and water efficiency in JGBG (36% and 15%) and LEED (32% and 9%) demonstrate the localisation of the standard as each reflects the scarcity of energy and water resources faced by Jordan [1,4]. However, the actual performance of green buildings in Jordan certified either by LEED or JGBG have never been evaluated systematically, hence this paper compares the performance between LEED and JGBG buildings in terms of indoor air quality and occupants’ absenteeism rate as representative metrics to investigate if the local rating system has a positive impact on the performance of building and their occupants.

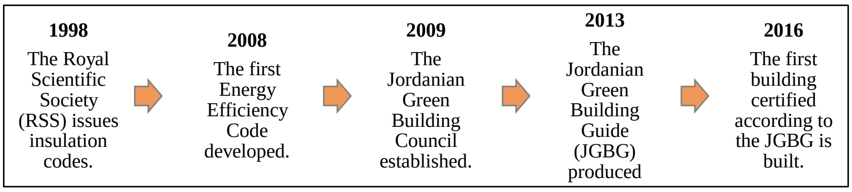

Figure 0.1 The green building developments in Jordan.

Table 0.1 The main attributes of LEED and JGBG.

Tool	Rating level	Flexibility	First version	Last version	Categories	Total points and % of total	
						LEED	JGBG
LEED	Certified ≥40 Silver ≥50 Gold≥60 Platinum ≥80	165 countries	1998	2013	Site selection	26 (23.6 %)	35 (14 %)
					Water efficiency	10 (9.1 %)	38 (15.2%)
					Energy efficiency	35 (31.8 %)	89 (35.6%)
					Material	14 (12.7 %)	36 (14.4 %)
					IEQ	15 (13.6%)	24 (9.6 %)
					Innovation	6 (5.5 %)	-
JGBG	A (≥80 points) B (70–79 points) C (60–69 points) D (50–59 points)	1 country	2013	2013	Recycled and pollution	4 (3.6 %)	-
					Building management	-	28 (11.2 %)
					Total points	110	250

B.5. Indoor air quality and absenteeism rate in green office buildings

The indoor air quality of office buildings is considered one of the most important factors affecting employee health. This is also known to affect the absenteeism rate due to an increase in sick leave. Carbon dioxide (CO_2) is a primary indicator of indoor air quality and the healthy workplace should have low CO_2 concentration above ambient levels, delivered through a high level of ventilation. However, the necessity to decrease energy consumption in green buildings has traditionally resulted in low rates of ventilation to avoid ventilation heat loss or gains. This tends to increase indoor CO_2 concentration that can affect occupant performance (Satish *et al.*, 2012).

In addition, high levels of indoor CO_2 concentration can be a reason for sick building syndrome symptom, CO_2 concentration more than 2,000 ppm causes deepened breathing; 4,000 ppm increases respiratory diseases; 10,000 ppm is associated with loss of consciousness and visual disorder; and 25,000 ppm can be a reason for death (Seppanen, Fisk and Mendell, 1999). Consequently, research has attempted to associate the CO_2 concentration in workplace with employee work performance(Vehviläinen *et al.*, 2016). For example, in a study comparing the absenteeism rates of occupants working in free-running and mechanically conditioned buildings in France, found that employees in the naturally-ventilated building had a lower rate of absenteeism compared to the employees in the mechanically-conditioned buildings (Teculescu *et al.*, 1998). These results support the idea that the indoor air quality of the workplace can affect employee health related indicators such as absenteeism.

B.6. Methods

B.6.1 Indoor Carbon dioxide (CO_2) measurement

Indoor CO_2 concentration was measured in the JGBG and LEED buildings (Figure 0.2 and Figure 0.3) in the winter of 2019 for five weeks (7th Jan – 14th Feb 2019) using Raspberry-Pi sensors (Figure 0.4). The Raspberry-Pi sensors were used as they have undergone rigorous testing and calibration, making them suitable for continuous measurements with good accuracy (±30 ppm) (Lovett *et al.*, 2016; Vellei *et al.*, 2016). The sensors were tested before starting the study. The data were logged at 5-minute intervals. The sensors were installed in the two buildings and located in the shared multi-occupant workspaces that have the most occupation density. They were placed in the middle of the monitored area at seated head height (0.9 m to 1.10 m). The employees were asked not to cover or touch the sensors during the monitoring period. Both buildings were in Amman, reducing logistical burden, and providing climatic homogeneity. The physical characteristics of the selected spaces in the two buildings were matched as closely possible:

- The volumes of the monitored rooms were approximately 216 m^3 (L= 12 m, w = 6 m, H = 3 m) and 210 m^3 (L= 10 m, w = 7 m, H = 3 m) in the JGBG and LEED buildings respectively.
- The occupancy area was 4 m^2 per occupant.
- The rooms have walls with low VOC paint, normal fixed double-glazed facades.
- The floors were covered with carpet; no moistures problems were reported in the buildings.
- There were no plants inside the monitored rooms.
- Active ventilation is used in both buildings designed to achieve (8.5 L/(s. person)) according to JGBG and LEED specifications.

Figure 0.2 The JGBG-Certified building.

Figure 0.3 The LEED-Certified building.

Figure 0.4 The CO_2 sensor.

B.6.2 Absenteeism rate measures

Participants were surveyed to measure the absenteeism rate in workplaces for 4 weeks using the well-tested and reliable Health and Performance Questionnaire (HPQ), developed by the World Health Organization (WHO) (Kessler, Petukhova and McInnes, 2007; Pournik *et al.*, 2012). As most of the participants speak Arabic as a first language, the questionnaire was translated to Arabic, tested using a pool of technically literate bilingual speakers at the University of Bath through re-translation to English. The survey was combined with a consent form and distributed in the monitored spaces. The sample consisted of 100 employees, 50 participants from each building. Before starting the study, the upper management of the buildings were contacted directly to obtain their consent, and ethical approval was obtained from the University of Bath. As both buildings in this study were used as workspaces, their occupants were involved in typical office tasks (i.e., computer typing, reading, writing, and occasional walking for document delivery or communication).

B.7. Results

Figure 0.5 shows the measured indoor CO_2 concentrations during 5 weeks in the monitored spaces. Data were cleaned and analysed using the statistical programming language R. Mean CO_2 concentration in the LEED building was higher (661ppm) compared to the JGBG building (470 ppm) during the working hours. A standard *t*-test at 99% confidence level suggests this is a significant difference ($p < 0.000$). Interestingly, there is a considerable temporal variation of CO_2 concentration between the two buildings.

Figure 0.6 presents the CO_2 concentration over a typical 24-hour period in both buildings. The indoor CO_2 concentration in the JGBG building is almost constant during the working hours (0700 to 1700 hours, mean = 456 ppm) meeting the JGBG specification of indoor CO_2 concentration in offices. It increases after working hours (1700 to 300 hours) peaking at 664 ppm. Conversely, the mean CO_2 concentration in the LEED building during working hours is higher (693 ppm), declining dramatically during the lunch break between (1300 to 1400 hours), and subsequently falling to 404 ppm after working hours. The above differences can be attributed to the different ventilation approaches that have been followed in the two buildings. The JGBG building is provided with a ventilation rate

30% above that corresponding to the minimum rate required by LEED, due to an IEQ requirement in JGBG. Mechanical Ventilation Heat Recovery System (MVHR) is used in the JGBG building, which provides a balance between saving energy and providing high indoor air quality. The efficiency of the MVHR can be controlled according to the occupancy level. Therefore, the efficiency is raised to the maximum during the working hours to ensure a continuous ventilation rate, while it is reduced after working hours, when the building is almost empty. In contrast, the LEED building is provided with a constant level of airflow around the day, and hence CO_2 concentration increases during the daytime because of human activity.

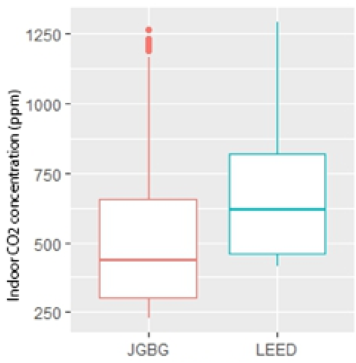

Figure 0.5 The indoor CO_2 concentrations in the monitored spaces during working hours over 5 weeks.

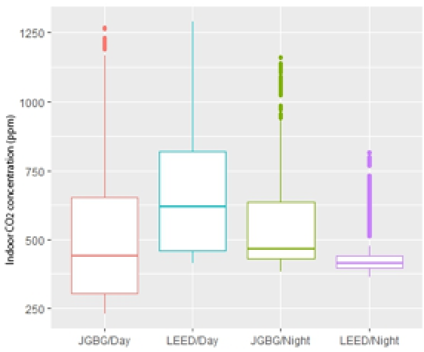

Figure 0.6 The indoor CO_2 concentrations in the buildings during a typical day (day/night).

Absenteeism is scored in terms of "hours lost per month", which is to say that a high score indicates a higher amount of absenteeism. The JGBG has a higher mean (206 h) of total working hours during 4-week compared to the LEED building (189 h) and compared to the expected working hours by the employer (180 h/ per 4-week). This is a statistically significant difference ($p < 0.03$) at 95% confidence level. The JGBG building reported lower mean (0.60) of missing days due to the sick leave in 4-week compared to the LEED building (mean = 2.6), and there was a significant difference between the two means ($p < 0.00$) at 99% confidence level. In addition, absolute absenteeism, calculated using the absenteeism score set by Health and Performance Questionnaire (Kessler, Petukhova and McInnes, 2007), was substantially lower in the JGBG building (by 9 hours) during the 4-week, compared to the LEED building. Of course, it is worth noting that we do not investigate causality for these results beyond those arising from the design, specification and operation of the building and there could be other factors at play that create these differences. This will require further investigation.

B.8. Conclusion

Indoor CO_2 concentration has often been used as an indicator of adequate indoor air quality, which affects occupants' health and performance. This paper aims to compare the performance of buildings built to the localised Jordanian Green Building Guide and the international LEED standard in terms of indoor air quality and occupant absenteeism rate. The results of this investigation show that there is a highly significant difference between the two means of the indoor CO_2 concentration between the two buildings during working hours.

The mean in the LEED building was higher compared to the JGBG building. However, the two buildings were within the recommended limits of CO_2 concentrations inside offices for an 8-hr workday under both LEED and JGBG specifications (1,100 ppm). Further, respondents who reported higher levels of absenteeism rate were working in the building that reported significantly higher levels of CO_2 concentrations during working hours. These results suggest that the development of local green assessment tool could bring better benefits to both building performance and occupants' performance, although this requires further investigation in more buildings over longer periods.

B.9. Acknowledgements

The authors would like to thank Baha Mualla for helping in collecting the data, and to thank the management of the office buildings for giving their consent to conduct this study. This work was supported by Al-Ahliyya Amman University in Jordan.

B.10. Postscript

This chapter compares the performance of the localised JGBG in Jordan to the imported LEED standard. The comparison consists of two levels, including building performance in terms of IAQ and occupant performance, i.e., absenteeism rate. Findings show that, although both green-certified buildings (i.e., LEED and JGBG) complied with the standards for indoor CO_2 concentration levels in workplaces, the employees in the JGBG-certified building had a lower rate of absenteeism compared to their counterparts in the

LEED-certified building. This chapter indicates that localised GBCs could bring better benefits to the building performance and occupants compared to the imported green codes.

Appendix C
Survey

Department of Architecture and Civil Engineering
UNIVERSITY OF BATH

We are conducting an evaluation of your office building to assess how well it performs for those who occupy it. This information will be used to assess areas that need improvement and provide feedback for similar buildings. Responses are anonymous, please answer all the relevant questions.

Organization name: Employee ID:

Date: Time:

Section I *(Please tick)*

a. Gender Male Female

b. Job category

Administrative	Sales	Design	Marketing	Executive	Other……………………………

c. How long have you been working at this organization?

<6 months	6 months to 1 year	1 year to 2.5 years	2.5 to 5 years	>5 years

d. What is your education level?

High school	college or 2-year degree	Holding B.Sc.	Holding M.Sc.	Holding Ph.D.

e. How long do you typically spend in the office during the day?

Hours	>1	1 - 2	2-3	3 - 4	5 - 6	7 - 8	>8

f. Your monthly income is ranged between (JD):

<400	400-700	700-1000	1000-1300	1300-1600	1600-2000	>2000	Others……………

g. How many people are working with you in the same office?

Only me (single)	2-3 (shared room)	4-9 (small open plan)	10-24 (Medium open plan)	>24 (large open plan)

h. If you have the ability to improve only one physical item (e.g., light, ventilation, temperature) in your workplace, what is this item? ……………………………………………………………………………..

Section II		Number of hours (00-97)
B3.	About how many hours altogether did you work in the past 7 days? (If more than 97, enter 97)	

B4.	How many hours does your employer expect you to work in a typical 7-day week? (If it varies, estimate the average. If more than 97, enter 97.)	
B5. Now please think of your work experiences over the past 4 weeks (28 days). In the spaces provided below, write the number of days you spent in each of the following work situations… In the past 4 weeks (28 days), how many days did you…		Number of days (00-28)
B5a	Miss an entire workday because of problems with your physical or mental health? (Please include only days missed for your own health, not someone else's health.)	
B5b.	Miss an entire workday for any other reason (including vacation)?	
B5c.	Miss part of a workday because of problems with your physical or mental health? (Please include only days missed for your own health, not someone else's health.)	
B5d.	Miss part of a work day for any other reason (including vacation)?	
B5e.	Come in early, go home late, or work on your day off?	
B6.	About how many hours altogether did you work in the past 4 weeks (28 days)? (See examples below.)	
Examples for Calculating Hours Worked in the Past 4 Weeks 40 hours per week for 4 weeks = 160 hours 35 hours per week for 4 weeks = 140 hours 40 hours per week for 4 weeks with 2 8-hour days missed = 144 hours 40 hours per week for 4 weeks with 3 4-hour partial days missed = 148 hours 35 hours per week for 4 weeks with 2 8-hour days missed and 3 4-hour partial days missed = 112 hours		

Section III

B9. On a scale from 0 to 10 where 0 is the worst job performance anyone could have at your job and 10 is the performance of a top worker, how would you rate the usual performance of most workers in a job similar to yours?

Worst performance										Top performance
0	1	2	3	4	5	6	7	8	9	10

B10. Using the same 0-to-10 scale, how would you rate your usual job performance over the past year or two?

Worst performance										Top performance
0	1	2	3	4	5	6	7	8	9	10

B11. Using the same 0-to-10 scale, how would you rate your overall job performance on the days you worked during the past 4 weeks (28 days)?

Worst performance										Top performance
0	1	2	3	4	5	6	7	8	9	10

Section IV *(Please tick)*

During the past 4 weeks (28 days), how many of did you experience the following symptoms while working in the office?		1. None of the time	2. A little of the time	3. Some of the time	4. Most of the time	5. All the time
1	Feeling dizzy					
2	Feeling tired or having low energy					
3	Back or neck pain					
4	Pain in your arms, legs, or joints					
5	Muscle soreness					
6	Watery eyes, runny nose, or stuffy head					
7	Dryness of the eyes					
8	Cough or sore throat					
9	Fever, chills, or other cold/flu symptoms					
10	Dry, itching or irritated skin					

Section V

a. Indoor air quality & ventilation

(Please rate your satisfaction of the following items)

The overall air quality of your office:

Dissatisfied						Satisfied
1	2	3	4	5	6	7

The fresh air in your office?

Dissatisfied						Satisfied
1	2	3	4	5	6	7

The air humidity in your office?

Dissatisfied						Satisfied
1	2	3	4	5	6	7

The ventilation in your office?

Dissatisfied						Satisfied
1	2	3	4	5	6	7

If you need to, are you able to: (Please click items you can control in your office)

open/ close Windows	open/ close curtains	on/off Lights	on/off Air condition	on/off Heater

Does the quality of the air in your office have a negative effect on your work performance?

Not significant						Very significant
1	2	3	4	5	6	7

b. Noise (Please rate your satisfaction of the following items)

The background noise in your office?

Dissatisfied						Satisfied
1	2	3	4	5	6	7

Does the distraction from noise in your office have a negative effect on your work performance?

Not significant						Very significant
1	2	3	4	5	6	7

c. Lighting (Please rate your satisfaction of the following items)

The natural light in your office?

Dissatisfied						Satisfied
1	2	3	4	5	6	7

The sun glare in your office across the whole year:

Dissatisfied						Satisfied
1	2	3	4	5	6	7

Does the quality of light in your office have a negative effect on your work performance?

Not significant						Very significant
1	2	3	4	5	6	7

d. Thermal comfort *(Please tick)*

At present, I **feel**:

English	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Arabic-classic	بارد جدا	بارد	بارد قليلا	مرتاح	دافيء قليلا	دافيء	حار
Arabic-Levantine	بردان كتير	بردان	بردان شوي	مرتاح	مشوب شوي	دافي	كتير مشوب
	-3	-2	-1	0	+1	+2	+3

At present, I would **prefer** to be:

English	Much cooler	cooler	A bit cooler	No Change	A bit warmer	Warmer	Much warmer
Arabic-classic	ابرد كثيرا	ابرد	ابرد قليلا	لاتغيير	ادفيء قليلا	ادفيء	دفيء كثيرا
Arabic-Levantine	ابرد كتير	ابرد	ابرد شوي	لاتغيير	ادفى شوي	ادفى	ادفى كتير
	-3	-2	-1	0	+1	+2	+3

Please rate thermal comfort satisfaction in your office

Dissatisfied						Satisfied
1	2	3	4	5	6	7

Does the temperature in your office have a negative effect on your work performance?

Not significant						Very significant
1	2	3	4	5	6	7

3. Your clothes at present: (Please tick)		4. What is your activity during the past 15 minutes? (Please tick)	
Short Sleeve shirt/blouse		Sitting (passive work	
Long sleeve shirt/blouse		Sitting (active work)	

Vest		Standing relaxed	
Trousers/long skirt		Standing working	
Shorts		Walking indoors	
Dress		Walking outdoors	
Pullover		Other………………	
Jacket			
Long socks			
short socks			
Tights			
Tie			
Boots			
shoes			
sandals			
head wear			
barefoot			

Instantaneous Measurements (for researcher only)

Air Velocity (ms^{-1})	
Air Temperature (°C)	
Relative Humidity (%)	
Globe temperature (°C)	
Mean radiant temperature (°C)	
CO_2 level (ppm)	
Outdoor Temperature (°C)	

Appendix D

Details of the used equipment

Two types of instruments were used to monitor thermal conditions and indoor CO_2 levels in buildings, the collected data have two themes as following:

1. **Time series data**: Raspberry-Pi based sensors are used to conduct longitudinal measurements. The devices are developed at University of Bath, and they were combined into two compositions. First device to monitor air temperature and relative humidity simultaneously, and the second device to monitor the level of indoor CO_2 concentration inside buildings (see Table D.1).

   All sensors were tested and calibrated before starting the fieldwork to ensure that all sensors are working and provide consistent readings. Sensors were calibrated using two approaches, first, sensor data were benchmarked using periodic spot measurements which complied with ISO7726 and ISO7730 using high quality instrument (SWEMA).

   Second, we tested all sensors between each other. Sensors were placed in unoccupied office room, with no operable windows or any source for heating, cooling and ventilation, sensors recorded thermal conditions (T_a + RH) and CO_2 for 24 hours, to assure accurate readings with ± 0.5 °C margin resolution. I observed a consistency between recorded data from all sensors except three sensors, which were excluded from our data later.

Table 0.1 The components of Raspberry-Pi based sensors.

Unit	Description	
AdaFruit DHT22	digital sensor to measure temperature and relative humidity.	
DS18B20	Waterproof compatible temperature sensor.	
Sensair K30	CO_2 sensor optimised for high response time and protected by a particle filter.	

2. **Periodic spot measurements:** They were conducted using two instruments as following:

(i) Delta HD 32.3 is used to monitor air temperature, relative humidity, mean radiant temperature and air speed, which are used to calculate the PMV. This instrument complies with ISO 7730 and ISO 7726 (Table D.2).

(ii) SWEMA is used to record thermal conditions and to benchmark the longitudinal sensor data as previously mentioned. This instrument complied with ISO7726 and ISO7730 (Table D.3).

Table 0.2 The components of Delta HD 32.3 instrument.

Unit	Description	
TP3276.2	Temperature probe has 5 cm diameter globe thermometer with Pt100 temperature sensor.	

HP3217R	Combined probe for temperature and relative humidity.	
AP3203.2	Probe with hot omnidirectional wire to measure air speed, with NTC 10kohm sensor type.	
HD 32.3	The main instrument which connects probes sensors and has the main interface.	

Table 0.3 The components of SWEMA instrument.

Unit	Description	
HygroClip2A-S (859447)	Used to monitor indoor air humidity and temperature using rotronic sensing element and digital calibration.	
SWEMA 03	Used to monitor air velocity and temperature, it consists of an omnidirectional anemometer that has sensitive microcontroller. It fulfils the ISO7726 requirements.	
SWEMA 05	It is a 15 cm diameter black globe temperature sensor, meets the requirement of ISO 7726.	
SWEMA Multipoint PC program	It has three separate windows: one for the setup and storing data in files, one for presenting data in online graphs and one ISO 7730 window.	

Appendix E

Department of
Architecture and
Civil Engineering
UNIVERSITY OF BATH

Consent to participate in the research

I understand that:

- I will take part in brief questionnaire surveys as part of the research.
- I am taking part in the Project on a voluntary basis, and I am free to withdraw from the research at any stage.
- My personal data will be held by the University and will not be disclosed to any third person. All results that are obtained using my data will be made anonymous.
- The results will be passed to upper management in aggregate form only and cannot be identified individually.
- My personal data will be held and stored securely and protected in accordance with the requirements of the Data Protection Act 1998.
- The objectives of this research have been explained to me.

Under these circumstances, I agree to participate in the Research, and I expressly consent to the University of Bath holding and processing my personal data for the purposes of the research project.

Name:
Signature:
Date:

Appendix F

Questions of semi-structured interviews

- How do you define green buildings?
- Do green buildings cost more than conventional buildings, and if so, why?
- What are the main drivers to build green buildings in the Middle East?
- In your opinion, what are the most important aspects of green building design?
- Do you think green certification can improve the occupants' experience inside the building?
- How do you think we can improve the indoor environment quality in green buildings?
- What do you think the relationship between the IEQ and occupant satisfaction?
- As an architect, how do you think we should develop the techniques of green building design towards a more comfortable indoor environment quality?
- What is the best method to assess the current green buildings in the Middle East?
- Why are not all buildings built to be green?

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